Charge transport in thin layers of organic crystals

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Abstract. Recently, the organic thin layers have been studied widely due to their good properties for application in field–effect transistors. In this paper we survey recent studies on carrier transport properties in such molecular layers which are promising for applying in transistors. First we present the main electronic properties of organic molecules forming layers or crystals and the relation of this properties on specific features of band structure of organic crystals. The layers of pentacene are studied particularly as an example. The crystal structure of this material is presented. The experimental methods of carrier mobility measurements in high resistivity layers studied are described. The experimental results are in agreement with Visenberg model of charge transport in non-ordered materials. We discuss the charge transport properties measured for single crystal transistors. The mobility in these crystals is significantly greater in comparison with layers particularly at low temperatures and shows an interesting anisotropy in respect to crystallographic directions.

1. Introduction
Organic conductors have been studied for a long time (e.g. anthracene since 1950). Organic crystals are formed by organic molecules bonded by Van-der-Waals forces. Therefore, the electronic properties of organic crystals are different from those in inorganic crystals, where bonds are of the ionic or covalent origin. The number of trapped states and strong electron-phonon coupling in organic crystals, and resulting from these the electronic, molecular and lattice polarisations determine charge transport properties via small polaron formation and a kind of many body interaction between them [1]. Thin layers of organic materials have crystal structure far different from single crystal one (epitaxial). There is a weak order, as well as a great number of defects. Thus, the electrical conductivity is hopping one instead of band-like. Nevertheless, even non-perfect organic layers are promising for field effect transistors production and the investigations of transport properties in such layers are carried out widely.

The desirable goal of material research in this field is increasing the charge mobility in p- tape as well as in n-type channel organic crystals. This can be attained not only by careful purifying or searching new materials but also by the crystal structure improvement of the layers for these materials. The pentacene as a p-type material shows the mobility in thin layers exceeding 1 cm²/Vs. In single ambipolar pentacene transistors the electron mobility also exceeds 1cm²/Vs. In other n-type channel organic materials the n mobility is restricted to 0.1 cm²/Vs for naphthalenetetracarboxilic materials and C60 and to 0.01 cm²/Vs for fluorinated copperphthalocyanine [2]. However, in ambipolar perylene single crystal layers, the electron mobility achieves the values 5.5 cm²/Vs at room temperature and 120 cm²/Vs at 50K [3]. In the paper [4] the Hall mobility 4 cm²/Vs in single crystals of bis (1,2,5-thiadiazolo)-p-quinobis(1,3-dithiole) (BTQBT) was reported, whereas in channel layers the field-
effect mobility was 0.044 cm$^2$/Vs [5]. The advantage of this material over pentacene is that the BTQBT planar molecules lie flat on substrates during organic molecular–beam deposition process [6].

The present paper is oriented mainly towards to the structure and charge transport properties of pentacene which seems to be the best candidate for channel organic material in field–effect–transistors [7, 8].

2. Electronic properties of free organic molecules and electronic structure of organic crystals

Isolated molecule is either in neutral or negative or positive ion state. The affinity energy $A$ (the energy liberated by the attachment of an electron by neutral molecule) and the ionisation energy $I$ are vertical or adiabatic $A_v$, $A_a$, $I_v$, $I_a$.

The terms of ionisation and affinity energy can be considered in the frame of the molecular orbitals theory [9]. The position of molecular energy levels of ionised molecule are shifted in respect to the levels in neutral molecule. This changing is particularly visible in aromatic hydrocarbons [10, 11]. Moreover, the intrinsic or extrinsing (medium) polarisation effects influence also the position of these levels e.g. for naphthalene $I_v = 9.30$ eV [11], whereas the experimental value for positive ionised molecule this energy is 8.15 eV. The difference arises from polarisation of the naphthalene molecule by positive space charge.

In molecular crystals the ionic molecular states form narrow bands due to forces forming the crystal (figure 1). Both $I_v$ and $A_v$ energies are released upon the taking the electron from the infinity and placing it in valence orbital of positive ion or on molecule respectively. Otherwise these energies should be inserting into system in order to the entire removal of an electron from valence orbital or from molecule. The additional electron on a molecule in a crystal gains the additional energy $P_c$ (polarisation energy ) forming lowest conduction level. Likewise, the molecule with a missing electron profits the additional polarisation energy $P_h$ in a crystal as well as forming the valence level. These two levels form energy gap $E_g$. However, it should be noticed here that the conduction and valence levels do not mean the delocalized carriers as they are in inorganic semiconductors. The carriers are strongly localised in a simple homomolecular organic crystals. There are two main reasons for strong localisation of carriers in those crystals: the high value of polarisation energies in aromatic hydrocarbons and the small nearest–neighbour interaction energy. In narrow-band semiconductors there is also high polarisation energy, but the inter-site energy is relatively much greater making the carriers mobile. Contrary, in wide–gap materials (Ge, Si) the polarisation energy is very small comparing to inter–site energy, therefore the carriers are free to.

It should be noticed however that not all organic crystals exhibit the same degree of localisation. The carriers on higher conducting levels show greater mobility.

![Figure 1. Scheme of energy levels of molecular crystals.](image-url)
The excitation charge–transfer levels (CT) in figure 1 represent the energy required for removing of the electron from one molecule and placing it on another one being nearest or next- nearest neighbour. These states were previously called ionic states [13] and are similar in the origin to the ordinary excitons, but here the hole-electron distance is now extended to one or more distances of lattice constant. The charge- transfer of neutral molecules forms electron- hole pairs in which electron and hole is more or less correlated depending on the distance \( r \) between them. For \( r \) sufficient small i.e. smaller from value \( r = kT \), the Coulomb interaction energy \( W_e \) correlates the electron-hole interaction energy providing the CT energy:

\[
E_{CT}(r) = I_g - A_g - P_{eh}(r) - W_e(r)
\]

where \( P_{eh} (r) \) is the polarisation energy of the electron–hole correlated pair. For \( r > r_c \) the CT energy is equal \( E_g \). Thus the energy gap is the minimal energy which forms uncorrelated electron-hole pairs in the crystal. The CT energies for aromatic hydrocarbon crystals decrease considerably with the increase of the number of benzene rings in linear molecule [14, 15, 16] (figure 2), e.g. this excitation is 4.38 eV in naphthalene [15] whereas in tetracene this energy is about 2.8 eV [14]. It should be expected that the lowest CT level in pentacene approaches the lowest conduction band level (Fig 2).

| E_g [eV] |
|---------|
| 5       |
| 4        |
| 3        |
| 2        |
| 1        |
| x 4.4eV (c) |
| x 4.4 eV (a) |
| x 4eV (d) |
| x 3.9eV (b) |
| 3eV (d) |
| 2.7-2.9eV (c) |
| x 3.1-3.5eV (d) |
| x 2.2eV (c) |
| x 0.7eV (e) |

**Figure 2.** Energy band gap in molecular crystals defined as a minimal energy necessary to induce electrical conductivity in a crystal \( (E_g = I_c - A_c) \).

The strong electronic polarisation effects in molecular crystals are bar for the one-electron approximation calculations of the band structure of excess carriers usually applied in inorganic crystals. The electronic polaron formalism which is rather many-electron approach should be applied for crystals in which the hopping time of carriers from one site to neighbouring one is slow in respect to response time of electron system \( (10^{-15} \text{ s}) \). The one-electron band structures for naphthalene, anthracene, tetracene and pentacene were calculated by Katz, Rice et al. [18, 19]. The one-electron crystal states were constructed from molecular orbitals of isolated molecules. The crystal potential was formed as a sum of neutral molecular potentials placed in the nodes of crystal lattice. As an example the band structure of electron and holes in anthracene crystal is presented in figure 3 [18]. The bandwidth depends clearly on the direction in \( k \) space; this feature is typical for all aromatic hydrocarbons. The effective mass is usually 5–20 times the effective mass of electron and holes in the bottom of the conduction band and the top of the valence band respectively.
3. Single crystal structure and anisotropy of carrier mobility

The kind of molecular packing in molecular crystals influences strongly on intrinsic transport properties. The overlap between electronic orbitals of nearest molecules in crystals seems to be very important factor in this matter. The overlap C–C would be the great for flat molecules packed as parallel stacking as in violanthrene crystals [20]. Such layered structure of a crystal should have good electronic properties at least in the plane of the layers. However the realization of such layered structure in organic crystals of acenes is not observed [21]. These grown in herringbone structure (see figure 4), forming monoclinic (naphthalene and anthracene [1]) and triclinic (tetracene [22, 23] and pentacene [8]) crystallographic systems. The inversion centre of molecules is placed in the corners of unit cell as well as in (1/2, 1/2, 0) point. The angle δ between molecular planes of non-equivalent molecules is in the range of 51.1 – 52.3° for different acenes. The angle between molecular axis and c axes is different for non-equivalent molecules as well.

The crystal structure of pentacene single crystals (figure 5) and layers was studied by Campbell [24, 25], Dmitrakopoulos [26], Luo [27] and Matteus [28, 8]. Matteus [8] obtained four different polymorphic structures of pentacene layers. These structures differ by d (001) values which were 1.41
nm, 1.4 nm, 1.50 nm and 1.54 nm. The interlayer space \(d\) (001) for single crystals is 1.41 nm independently on a method of crystal growth.

![Figure 5. Scheme of pentacene crystal structure.](image)

Herringbone structure of aromatic hydrocarbon crystals is in tight relation to hydrogen–hydrogen and hydrogen–carbon electronic state interactions. The overlap of these states from neighbouring molecules depends on the structure. Thus the anisotropy of charge carrier properties should be expected. For pentacene single crystals the anisotropy of hole mobility was investigated by Schon, Kloc and Battlog [7]. Single crystals of pentacene were grown by vapour transport in hydrogen stream. Electrical properties were studied by current–voltage characteristics at wide range of temperature 2–500 K. The conductivity was greater in the plane parallel to the growth surface compared to that in the direction perpendicular to the a–b layers of the crystals. In the plane a–b the mobility of holes was approximately 2.9, 3.2, 2.3 \(2.20 \text{ cm}^2/\text{Vs}\) for directions forming angle 0, 30, 60 and 90° respectively with b axis. The anisotropy is visibly easy. The higher mobility was in the direction 30° in respect to b axis.

A strong mobility anisotropy on the growth surface of rubrene single crystals was studied by researchers in Ref. [29]. Here the PDMS stamp technique [30, 31] was used to fabrication FET structure on the surface of the rubrene crystals with various orientation of the channel in the plane a-b. The mobility was determined from I-V FET characteristics. The highest mobility almost 3 \(\text{cm}^2/\text{Vs}\) coincides with \(\text{b}\) direction whereas in \(\text{a}\) direction this value is 4 times lower. Studies of the anisotropy of mobility in perfect single crystals are crucial for observations of the nature of electrical conductivity in organic crystals and layers. The measurements on thin-film organic field effect transistors never show such anisotropy due to a number of structural defects as grain boundaries. Rubrene is conjugated chain with non-planar side molecules. The single crystal structure is herringbone to. The high mobility of this crystals may be attributed to the better overlap of the electronic orbitals of adjacent molecules.

4. **Theory of hole mobility in FET with non–single crystal layer**

Two basic theoretical models of charge transport in organic layers are usually proposed: of hopping and band–like transport. In such crystals the transport properties depend strongly on a nature, number and distribution of traps. The traps originate in a point and extended crystal structure defects. The self–trapping of charges also contributes to the conductivity of the organic crystals. This type of trapping occurs usually in crystals with narrow conductivity band. Self trapping can occur by optical modes of phonons or by acoustic modes.

The dependence of the field effect mobility on the temperature and gate bias for good ordered organic layers was proposed by Horowitz et al. [32]. The model bases on multiple trapping and release of charge carriers which transit to the extended levels in transport band i.e. to the valence band in the case of hole carriers. Thus the band model of conductivity takes place. The concentration of the band carriers depends on the energy levels of localised states, the temperature and the applied voltage. In non ordered, amorphic or pury ordered layers there are only strongly localized states. There, the charge transport is expected to be hopping one only. Vissenberg and Matters [33] calculated field effect mobility for such case using variable–range hopping idea [34]. The main assumption of the
model is that the transport properties are determined by the tail (for sufficiently low temperatures \( T < T_0 \) and low carrier densities) of the density \( g(E) \) of states

\[
g(E) = \frac{N_t}{k_B T_0} \exp \left( \frac{E}{k_B T_0} \right), \quad (-\infty < E \leq 0),
\]

(2)

where \( N_t \) is concentration of states.

Taken into account the Fermi–Dirac energy distribution \( f(\varepsilon, \varepsilon_F) \) of the carriers as well as the percolation theory [35] the authors of ref [33] obtained the Arrhenius–like behaviour of the conductivity versus temperature \( \sigma \propto \exp(-E_a/k_B T) \):

\[
\sigma(\delta, T) = \sigma_0 \left( \frac{\pi N_t \delta(T_0 / T)^3}{(2\alpha^3 B_c \Gamma(1-T/T_0)\Gamma(1+T/T_0))} \right)^{T/T_0}
\]

(3)

where \( \delta \) is a fraction of states occupied by carriers, \( B_c \) is percolation criterion [36, 37] of the system and \( \Gamma \) function

\[
\Gamma(z) = \int_0^\infty dy \exp(-y) y^{z-1}
\]

(4)

is in relation to the occupation number \( \delta \)

\[
\delta = \frac{1}{N_t} \int d\varepsilon \, g(E) f(\varepsilon, \varepsilon_F) \simeq \exp \left( \frac{\varepsilon_F}{k_B T_0} \right) \Gamma(1-T/T_0)\Gamma(1+T/T_0).
\]

(5)

The formulae (3) points on the nonlinear dependence of conductivity on carriers density \( N_t \delta \) (the linearity gives models with Boltzmann carrier distribution)

\[
\sigma \propto (\delta N_t)^{T_0/T}
\]

(6)

It should be notice that temperature dependence of conductivity (3) is in contrast with Mott behaviour \( \sigma \propto \exp\left[ -\left( T_1 / T \right)^{1/4} \right] \) obtained also for variable–range hopping but with constant DOS [34].

Basing on the model of conductivity presented above, Vissenberg and Matters [33] gave the temperature and voltage dependence of mobility of carriers measured by FET method. The gate voltage \( V_g \) induces in semiconductor layer the potential \( V(x) \) in the distance \( x \) from interface insulator–semiconductor modifying carrier distribution \( \delta(x) \) in semiconductor

\[
\delta(x) = \delta_0 \exp \left( \frac{eV(x)}{k_B T_0} \right)
\]

(7)

The field–effect mobility depends on gate bias as [38]

\[
\mu = \mu(V_g) = \left( \frac{L}{ZC_I V_d} \right) \frac{\partial I_{sd}}{\partial V_g} |_{V_d \rightarrow 0}
\]

(8)

where \( I_{sd} \) is source -drain current and gate biases are negative and greater then \(-2V\).

The resultant source-drain current for the case of distance dependence charge distribution \( \delta(x) \) is

\[
I_{sd} = \frac{WV_D}{L} \int_0^l dx \sigma[\delta(x), T]
\]

(9)

where \( L \) is the length, \( W \) is the width and \( t \) is thickness of the channel.
From (7), (8) and (9) the field effect mobility has been obtained [33]:

\[
\mu_{FE} = \frac{\sigma_0}{e} \left( \frac{\pi (T_0 / T)^3}{(2\alpha)^3 B_\alpha \Gamma (1 - T / T_0) \Gamma (1 + T / T_0)} \right)^{T_0 / T} \left[ \frac{(C_j V_G)^2}{2 k_B T_0 e_s} \right]^{T_0 / T - 1}
\]

(10)

where \(\alpha^{-1}\) is overlap parameter.

5. Methods of mobility measurements

Three basic methods of charge carriers mobility measurements are implemented for materials with high resistance: 1) time of flight (TOF) spectroscopy, 2) current voltage characteristics and 3) field effect transistor characteristics.

Time of flight spectroscopy bases on measurements of electrical currents caused by photoexcitation of electron-hole carriers near the surface of the crystal placed in applied electrical field. The short pulse (nanoseconds) laser light is used for excitation of carriers. The wavelength of light should be adjusted to its absorption in thin, near the surface layer of the sample. Polarity of the voltage applied selects the type of carriers. The carriers pass the width \(L\) of crystal in transient time \(\tau\), which can be determined from the shape of decay signal. The mobility is calculated for trap free crystals as

\[
\mu = \frac{L}{E \tau}
\]

where \(E\) is applied field. For the case with shallow traps having energy \(E_t\) and density \(N_t\) the measured mobility \(\mu_m\) is in the following relation to the ideal free mobility \(\mu\):

\[
\mu_m(T) = \frac{\mu(T)}{1 + (N_t^+ / N_v)[\exp(E_t^+ / k_B T) - 1]}
\]

(11)

This method can be used for bulk materials of very good crystallinity, nevertheless it has some advantages in respect to classical methods: the results of TOF method are free from contact influences [39].

The second method: the space charge limited I–V characteristics is based on general equation for current \(J\) in unipolar (hole) sample caused by electric field

\[
J = \mu \rho_f F - D \frac{d \rho_f}{dx}
\]

(12)

where \(D = \mu k T / E\) is the Einstein diffusion coefficient and \(\mu\) is the mobility of the carriers. The electric field have to fulfill Poisson’s equation

\[
\frac{d F}{dx} = \frac{\rho}{\varepsilon e_0}
\]

(13)

where \(\rho\) is total charge density i.e. the sum of free carriers \(\rho_f\) and trapped one \(\rho_t = \rho_f + \rho_i\). The free carriers density depends on total density as well as on the position \(x\): \(\rho_f = \rho_f (\rho, x)\).

The simplest solution of equation (12) is given by Mott and Gurney [40] for the case without traps and ignoring diffusion

\[
J = \frac{9}{8} \mu \varepsilon e_0
\]

(14)

This solution is a Child Low and it determines the space charge limited current (SCLC). The solutions for various cases of trapping were given by Bonham and Jarvis [41]. These cases are listed in Table 1. For shallow traps with exponentially distributed energy the current density is the square dependence on the applied voltage \(U\) as well. However the constant trapping factor \(\Theta\) plays significant role:
\[ J = \frac{9}{8} \mu_0 \varepsilon_0 U^2 \frac{L^2}{L^3} \]
\[ \Theta = \frac{N_V}{H_i} \exp \left( - \frac{E_t}{kT} \right) = \theta \]

where \( N_V \) and \( H_i \) is total density of states and traps respectively.

At the sufficiently large voltage above trap–filled voltage \( U_{TF} \), the Fermi level is shifted towards valence band over-passing trap levels and is making charge carrier free. In result the rapid increase of the current is observed. The symmetry of models is presented in table 1 and pictorial presentation of I–V characteristics is shown in figure 6.

### Table 1. Currents in I–V characteristics.

| Model                  | Assumptions | I(V) dependence | Descriptions               |
|------------------------|-------------|-----------------|----------------------------|
| Matt and Gurnay [40]   | - trap–free | \( J = \frac{9}{8} \mu_0 \varepsilon_0 U^2 \frac{L^2}{L^3} \), where \( \theta = \frac{\rho_f}{\rho} = \theta = \text{const} \) | \( U = \frac{W}{e} - V \) |
| Bonham and Jarvis [41] | - traps are shallow | \( \Theta = \frac{N_V}{H_i} \exp \left( - \frac{E_t}{kT} \right) \) | \( H_i \) - total density of traps uniformly distributed in a crystal |
| Helfrich and Mark [58, 59, 41] | - traps density depends exponentially on the trap energy | \( H(E_t) = \frac{H_i}{kT} \exp \left( - \frac{E_t}{kT} \right), l > 1 \) | \( E_t \) - energy of trap calculated from the top of valence band (\( E = 0 \)) |

Thirst’s method allows to determine the mobility of carriers from electrical characteristics of field effect transistor in which the organic material studied plays the role of active layer. Figure 7 shows the geometry of the thin film field effect transistors (figure 7a) and field effect transistor made on single crystal (figure 7b). A typical current-voltage characteristics for field effect transistors are presented in figure 8, where figure 8a shows the dependence of current drain–source \( I_{ds} \) versus voltage drain-source \( V_{ds} \) for different gate voltage \( V_g \). In figure 8b the dependence of saturated current \( I_{ds} \) on \( V_g \) is shown as well. The field effect mobility \( \mu_{FE} \) can be determined from the slope of a plot in figure 8b. According to the formulae [42]:

\[ I_{ds,s} = W / 2 LC_i \mu_{FE} (V_g V_{th})^2 \]

where \( W \) and \( L \) is width and length of channel and \( C_i \) is a capacitance of insulator (per unit area).
6. Charge transport properties of pentacene films

Pentacene is promising material for organic electronic devices [43, 44, 45, 46]. The structure and ordering of pentacene thin films depend highly on a growth method. The crystal defects, grain boundaries and disorder dominate charge transport properties in layer obtained. Therefore the structural quality determines the type of transport and its temperature behaviour. In ultra pure single crystals the band like transport is observed at low temperatures whereas at high temperatures it crosses over to hopping mechanism [7, 47]. The same behaviour would be expected in epitaxial layers of pentacene. However, single crystalline layers of pentacene has not grown so far. Brown et al. [38] obtained layers using precursor method (figure 9). Films deposited were composed of microcrystallites. The transport properties depends strongly on conversion temperature and the best mobility of $0.03 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ was observed for conversion temperature of 180°C.

![Figure 6. One carriers I–V characteristics for a) one trap level and b) two trap levels.](image)

![Figure 7. Scheme of field effect transistor.](image)

![Figure 8. Current-voltage characteristics of field effect transistor.](image)
The temperature dependence of the field–effect mobility $\mu_{FE}$ on temperature in these layers is justified very well [33] (figure 10a) by formulae (10) describing theoretically hopping mechanism of conductivity presented in previous section. The experimentally determined activation energy as a function of gate voltage is also in agreement with prediction by formulae (10) [33] (see figure 10b). The parameters of fitting shown in figure 10 are $\sigma_0 = 1.6 \times 10^{10} \text{s/m}$, $\alpha^{-1} = 0.22 \text{nm}$, $T_0 = 385 \text{K}$ [33].

Mattheus [8] investigated pentacene layers formed by high vacuum evaporation on highly doped silicon (gate) wafers with 1$\mu$m SiO$_2$ layer as an insulator (see figure 7). The 1.54 nm polymorphic pentacene was studied by I–V characteristics of FET. The charge transport properties were determined from linear part of the characteristic [42]. The mobility was calculated from channel conductance $g_C$

$$g_C = \left. \frac{\partial I_{sd}}{\partial V_{sd}} \right|_{V_G} = \frac{Z}{L} \mu C_f (V_g - V_T)$$

(18)

The temperature dependence of mobility in the range of temperature 145–300 K was measured as well. These results point on the almost independence of mobility on the temperature. The value of mobility was in the range $1.0 \pm 3 \times 10^{-2} \text{cm}^2/\text{Vs}$.

Stadlober et al. [48] studied the influence of polymorphism, grain size and film thickness on electrical properties of pentacene layers deposited in high–vacuum conditions in the standard FET geometry device with organic PVP or PMMA dielectric layers. The mobility in layers composed in grains with size below 1$\mu$m was $10^{-2} \text{cm}^2/\text{Vs}$ whereas for 1$\mu$m grains this mobility increased steeply and stayed stable (0.35–0.4 cm$^2$/Vs) for layers with larger grains. This interesting result would be explained by assumption that the mean free path of carriers is about 1$\mu$m. Then the grain boundary scattering is greater for layers composed of smaller grains. It was also noticed that the mobility depends on the layer thickness. It was the same for layers having thickness up to 150 nm. For thicker films the mobility decreases probably due to higher resistance of contacts or to the presence of the bulk phase inclusions in the layer. From this the authors concluded that the bulk phase had smaller intrinsic mobility.
Table 2. Semiconductor polymer materials applied in organic FET.

| Polymer                   | Symbol | Molecule | Mobility $\mu$ (300K) [cm²/Vs] | Ref. |
|---------------------------|--------|----------|--------------------------------|------|
| Thienylene-vinylene oligomers | TVB    | ![TVB structure](image) | $10^{-5}$ – $10^{-3}$ | [52] |
|                           | TVC    | ![TVC structure](image) |  |  |
|                           | TVD    | ![TVD structure](image) |  |  |
| Thienylene-vinylene-thienylene | TVT    | ![TVT structure](image) | $1.1 - 5.1 \cdot 10^{-5}$ | [53] |
| Polythienylene-vinylene | PTV    | ![PTV structure](image) | $10^{-4}$ – $10^{-3}$ | [38] |
| Poly (β'-dodecyloxy (-α, α’-α, α'') tertienyl (poly DOT₃) | DOT₃   | ![DOT₃ structure](image) | $10^{-6}$ – $10^{-4}$ | [54], [55] |
| Rubrene                  |        | ![Rubrene structure](image) | 15 (single crystal 300K) | [29], [31] |
| Perylene bulk            |        | ![Perylene structure](image) | hole 0.4 electr. 5.5 | [3] |
| Pentacene film           |        | ![Pentacene film structure](image) | 0.7 | [49] |
| Pentacene bulk           |        | ![Pentacene bulk structure](image) | 2, 0.1 | [56], [57] |
| Bis (1,2,5-thiadiazolo)-p-quinobis (1,3-dithiole) | BTQBT  | ![BTQBT structure](image) | 3.2 | [7] |
|                          |        |          | 0.044 | [5] |
7. Conclusions

The recent interest of the progress in organic electronic is focused towards thin film transistors with active semiconductor layer formed from flat oligomeric molecules. The great progress was achieved in increasing of charge carrier mobility in layers: up to the value about 1 cm$^2$/Vs in pentacene [48, 49, 50]. Paralelly, the studies of single crystals of organic materials with high mobility are developed strongly in the aim to research the mechanisms of the electronic transport not limited by structural defects. Several works reported optimistic results. In tetracene single crystals the mobility of 1 cm$^2$/Vs was measured and in paper [7] the mobility in single pentacene crystals reaches the value 3.2–4 cm$^2$/Vs at room temperature and 40000 cm$^2$/Vs at 5K. Schon, Kloc and Batlogg [3] reported 5.5 cm$^2$/V cm in perylene at room temperature. In rubrene single crystals the mobility was measured 7.54 cm$^2$/Vs at room temperature [51]. However, the carrier mobility in layers of organic materials is still far less then these for single crystals (see table 2). The reasons are defects, disorder, grain boundaries. The main mechanism of charge transport is hopping. Some cases of crossover to band like model are observed only for single crystals [7]. The charge transport in such structures is far from full understanding. The dominated molecular orbital overlap mechanism needs further studies. The temperature dependence of mobility in layers usually varies for samples even forming in the same growth conditions with strongly technological parameters imposed. Generally it seems that the transport properties in layers is not bulk effect [48]. The interface semiconductor–insulator and the first layer are particularly important in conduction. Therefore the study of crystal structure of layers and the initial stage of layer forming should be investigated carefully in the aim to understand better conductivity properties and to reach effort in the increase of mobility. Therefore, the searching of new organic materials consisting of planar molecules, which would lie flat on the substrate in the deposition process, seems to be also promising direction of research [5].

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