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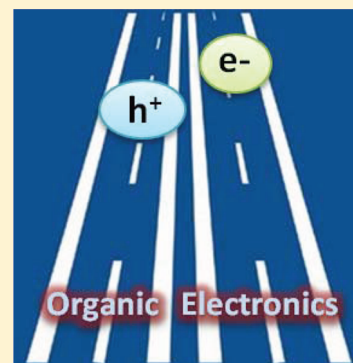
# Organic Semiconductors toward Electronic Devices: High Mobility and Easy Processability

Constanza Ruiz,<sup>†</sup> Eva M. García-Frutos,<sup>†</sup> Gunther Hennrich,<sup>‡</sup> and Berta Gómez-Lor<sup>\*,†</sup>

<sup>†</sup>Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, 28049 Madrid, Spain

<sup>‡</sup>Departamento de Química Orgánica, Universidad Autónoma de Madrid, 28049 Madrid, Spain

**ABSTRACT:** Chemists worldwide are making strong efforts toward finding an organic semiconductor with optimum charge-transport stability and processability properties, approaching the problem from several angles. The number and variety of organic semiconductors have expanded exponentially during the past few years, allowing their classification and identification of the advantages and drawbacks of the different candidates, and leading to an increasingly better understanding of factors affecting charge carrier mobility. In this Perspective, we present different types of materials available, classified according to their supramolecular order. As it will be shown, high intermolecular order, although beneficial for charge transport, may compromise processability. The required balance between processing and high mobility can be achieved only through an adequate design at both the molecular and supramolecular levels.



Organic electronics has progressed rapidly over the past few years, with devices such as organic light-emitting diodes (OLEDs) already entering the market and the realization of efficient prototypes of OFETs, solar cells, or sensors. Many other applications are continuously being envisioned such as e-paper or radio frequency identification tags, considering the opportunities offered by organic materials to build large area, lightweight, flexible devices but mostly driven by a promise of low processing costs by methods such as printing or solution/melt deposition.

All of these devices involve charge transport as the main process in their operation. The efficiency of charge transport<sup>1</sup> within the organic semiconducting materials, quantified by the charge carrier mobility, plays a key role in the performance of the devices. Charge carrier mobility  $\mu$  reflects the speed of the holes/electrons under an electric field according to the relation  $v = \mu E$ .

Great advances in this area have been connected to the continuous increase in the charge mobility in semiconducting materials, which has reached values already surpassing that of amorphous silicon currently employed in commercial flat-panel displays (approx.  $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ). While these mobility values are already acceptable for many of the intended applications, the use of organic molecules in the fabrication of devices still suffers from serious limitations mostly derived from problems of stability and processability. There is still a clear need for efficient candidates that meet the requirements necessary for the high throughput development of devices.

The essential electronic feature that all organic semiconductors share in common is the  $\pi$ -extended aromatic systems that provide highly mobile electrons. Electron-rich  $\pi$ -conjugated molecules generally act as p-type semiconductors, i.e., the currents are due to holes. Organic n-type semiconductors are much scarcer than p-type semiconductors.

Negative charge carriers (electrons) can be injected and transported in inherently electron-deficient molecules or by appending electron-withdrawing groups to  $\pi$ -conjugated systems that would otherwise be hole transporters. Unfortunately, in most of the known n-type materials at ambient conditions, charge carriers are easily trapped by common environmental oxidants, such as oxygen or water.

In the quest for high mobility systems, the lack of a complete understanding of the charge carrier transport mechanism in

**In the quest for high mobility systems, the lack of a complete understanding of the charge carrier transport mechanism in organic semiconductors poses an important limitation.**

organic semiconductors poses an important limitation. Transport models<sup>1</sup> have been proposed in two extreme regimes depending on the degree of order of the materials: A band-like transport that would operate in highly purified single crystals, and a hopping regime in which polarons jump from one localized site to the next one, that would operate in amorphous and polymeric materials. However, single crystalline semiconductors are affected by dynamic disorder caused by nuclear motions, while high-mobility polymeric semiconductors present large crystalline domains, making neither an idealized band nor

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a polaronic model applicable.<sup>2</sup> Models bridging between two limiting behaviors have been proposed, but in spite of the important current activity in the field, the transport mechanism is still under debate.<sup>3,4</sup>

Independently of the type of transport considered, the magnitude of the electronic coupling (transfer integral), which expresses the ease of transfer of a charge between two adjacent molecules, plays a key role in the understanding of charge transport properties.<sup>1</sup> Electronic coupling is highly sensitive to the relative positions of interacting units, and therefore the efficiency of charge transport is closely related to the extent of molecular order in the bulk material. However, supramolecular organization may compromise the processability of organic semiconductors. Thus, while perfectly ordered, closely packed molecules found in single crystals have demonstrated impressive high mobilities, these materials are fragile and brittle and difficult to process. In contrast, amorphous and solution processable polymeric semiconductors meet the manufacturing requirements for low-cost electronics, but in these materials mobilities are low due to their inherent disorder. An intermediate situation can be found in liquid crystals, soft and self-organized states of matter, characterized by a dynamism that facilitates processing of the materials, while maintaining a significant supramolecular order.

In this Perspective, we highlight recent progresses in the development of new high mobility organic semiconductors. The advantages and drawbacks of different types of materials, classified according to their supramolecular order, are presented with the final goal to lead to a better understanding of the factors that affect the charge-carrier mobility. Supramolecular

*Crystalline Semiconductors.* As previously mentioned, the charge transport in organic semiconductors is directly related to their supramolecular order, and the highest mobilities so far have been found on ordered crystalline materials with molecular packing and crystallinity having a critical influence in their performance. A clear example is found in pentacene **1** (Figure 1), the prototype of a high mobility system that presents mobilities over  $1\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$  when measurements are performed on well-oriented crystalline films<sup>5</sup> but is practically insulating in amorphous films.<sup>6</sup>

In spite of being probably the most studied organic semiconductor, pentacene has major drawbacks that prevent its practical applications, such as instability in air and low solubility in organic solvents. Low solubility is a common problem found in organic semiconductors that, on the other hand, tend to self-organize into well-ordered polycrystalline thin films upon thermal vacuum evaporation. Thin film devices based on crystalline materials are mostly prepared by vaporization of the semiconductors and condensation onto the desired substrate. Molecular ordering, crystallinity degree, grain size, film morphology, or orientation of crystalline domains are critical to determine mobility and have to be tuned by optimizing different parameters such as the deposition rate, substrate temperature, etc. In addition, the need of an evaporation step eliminates much of the advantages of organic electronics that promise the fabrication of devices by using simple printing techniques.

Many efforts in the field have been focused on finding organic semiconductors with better solubility and higher stability. A particularly successful example is triisopropylsilylthynyl pentacene (TIPS) **2** (Figure 1) developed by Anthony et al.<sup>7</sup> In addition to providing a high degree of solubility in common organic solvents, the functionalization of pentacene at the central ring protects the molecules from oxidation and is beneficial for the molecular packing in the solid state by forcing molecules in a stacked arrangement favoring  $\pi$ - $\pi$  interactions.

The search for organic semiconductors with superior properties has also involved skeletal modification of acenes. For example, the replacement of the benzene rings of pentacene by thiophene rings **3**–**5** enhances the air stability,

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order, processing, and performance are directly influenced by each other. We describe attempts aimed to achieve the delicate trade-off between processing and performance required to allow organic semiconductors to enter massively in the market.

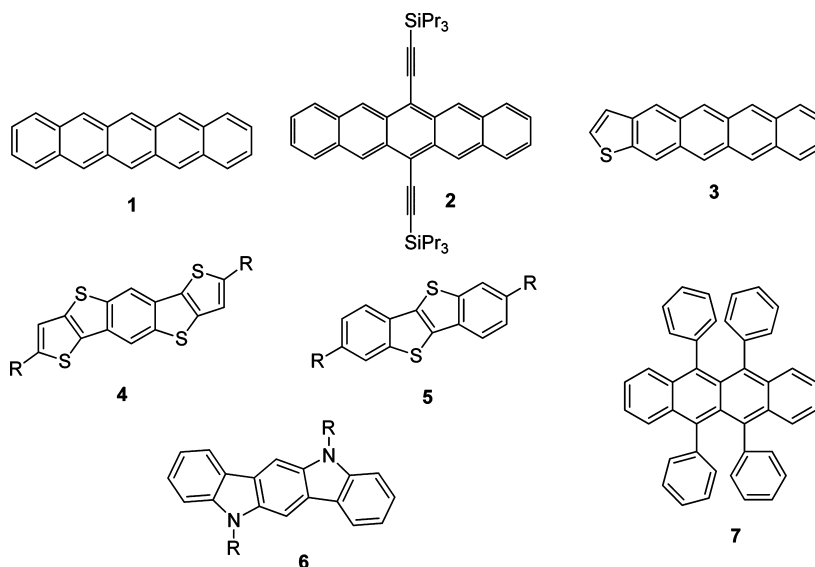


Figure 1. Chemical structure of different acenes and heteroacenes.

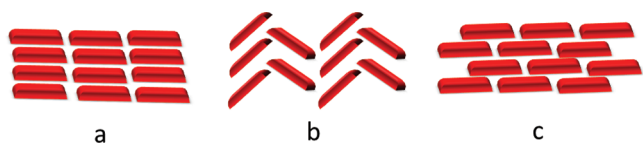
which has been ascribed to the lowering of the highest occupied molecular orbital (HOMO) level.<sup>8,9</sup> Benzene rings of pentacene have also been replaced by pyrrole rings like in indolocarbazole **6**. The advantage of this approach is the chemical versatility that offers the presence of nitrogen atoms in the aromatic core to further tune electronic properties, solubility, or crystalline packing through *N*-functionalization.<sup>10</sup>

Among heteroacenes, special attention must be paid to diacene-fused [1]benzothieno[3,2-*b*]-thiophenes **5** first introduced by Takimiya et al.<sup>11</sup> Attachment of long alkyl chains in positions 2 and 7 led to soluble compounds that show good air stability. In these materials, more polarizable sulfur promotes enhanced intermolecular overlap and electronic dimensionality, resulting in mobilities over  $1\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$  by simple spin coating and annealing.<sup>12</sup> This value could subsequently be considerably enhanced in different derivatives by optimization of processing conditions, confirming the benefits of this structural motif in the construction of high-mobility semiconductors.

The availability of soluble semiconductors allows the use of solution processes that involves coating of a solution of the semiconductor on a substrate (by spin-coating, drop casting, printing, etc.) followed by evaporation of the solvent, while molecules initially independently dispersed in the solvent self-organize in crystalline domains. Like evaporation techniques, solution processes usually lead to polycrystalline thin films, with microstructure characteristics that have to be carefully tuned for each device by varying parameters such as concentration, solvent, temperature, or evaporation rate.

Molecular disorder and barrier-like grain-boundaries in both solution and vapor processed polycrystalline thin films can localize and trap the charge carriers<sup>13</sup> and are major obstacles to achieve high charge carrier mobilities. These problems are not present in single crystals characterized by an enhanced extent of molecular ordering. In particular, rubrene **7** single crystals showed the highest mobility among organic semiconductors (above  $20\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$ ).<sup>14</sup> Charge transport in rubrene has been found to be highly anisotropic. By identification of crystal axes, it has been possible to assess that highest mobility occurs along the direction of strongest electronic coupling in which molecules organize in a shifted coaxial arrangement.<sup>15</sup>

After pioneer work in the study of the mobility anisotropy found on rubrene, many single crystalline semiconductors have been investigated in order to rationalize performance in terms of favorable crystallographic packing essential to design new promising materials. Face-to-face  $\pi$  stacking motifs (Figure 2a)



**Figure 2.** Schematic illustration of common crystal packing motifs: (a) cofacial, (b) herringbone, (c) “brick-wall”.

are proposed to be more efficient for charge transport than commonly found edge-to-face herringbone packing structures (Figure 2b) as a result of enhanced  $\pi$ - $\pi$  overlap and, consequently, an increased electronic coupling between neighboring molecules within the stacks. Brick-wall (Figure 2c) arrangements are also very promising to achieve high mobility structures by increasing the dimensionality of charge transport and rendering the systems less sensitive to charge-traps.<sup>16</sup>

Joined efforts, involving a tight cooperation between synthetic chemists, theoreticians, and experimental physicists, have offered an increasing understanding of the most important parameters for charge transport by providing justification of experimentally observed semiconducting performance. Recently it has been shown that theoretical predictions on not-yet-synthesized materials can also be successfully used to identify novel semiconductors. For example, an *in silico* screening led to the selection of the optimal candidate **8** (Figure 3) among different potential derivatives of dinaphtho-[2,3-*b*:2',3'-*f'*]thieno[3,2-*b*]thiophene.<sup>17</sup> Synthesis and characterization confirmed **8** as a new high-performance organic semiconductor presenting a mobility higher than  $10\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$ .

While many recent efforts have resulted in new methods for patterning organic single crystalline semiconductors, which have enabled, for example, direct deposition of large arrays of organic single crystals onto prefabricated transistor source-drain electrodes,<sup>18</sup> fabrication of devices from single crystals often requires manual selection and placing of individual crystals. For that reason, single crystals have not been traditionally meant to be incorporated in commercial devices, but to serve as model systems and to provide a well-defined structure in which the intrinsic electronic properties can be measured. This situation has changed dramatically over the last year with the development of solution processing techniques intended to obtain single crystalline thin films with enhanced molecular ordering that have led to impressive mobility values. For example, by directing the gradual shift of the liquid-atmosphere boundary upon evaporating a solution of **9** (Figure 3), a single crystalline domain could be obtained with a benchmark mobility of  $10\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$ .<sup>19</sup>

In another recent example, triisopropyl pentacene **2** was processed by a mechanical shearing technique that resulted in a strained lattice and, consequently, an increased mobility ( $4.6\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$  for strained versus  $0.8\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$  for unstrained films).<sup>20</sup> During processing, a shearing plate drags the solution across a heated substrate while keeping the bulk of the solution between the plate and the substrate, with only the evaporation front exposed. Triisopropyl pentacene domains with lengths of up to 1 cm are observed with the long axis parallel to the shearing direction.

Hasegawa et al. reported a method directed to combine the best of the single crystal electronic properties and the ease of the thin film fabrication by inkjet printing technologies.<sup>21</sup> By mixing fine droplets of a solution of the active semiconducting component and an antisolvent within a confined area, uniform single crystalline films of **10** have been successfully printed. The gradual growth of the single crystalline film has been possible because of the fluidic nature of the microliquid droplet in which laminar flow dominates over turbulent flow. Thin films transistors prepared by using this technique present average carrier mobility as high as  $16.4\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$ . Important sample-to-sample deviations are however found, indicating that optimization of this method is still necessary.

All these recent results hold great promise in the search of high-mobility solution-processed devices. However, preparation of single crystalline thin films requires careful control of different nucleation parameters highly sensitive to subtle variations, and the generality of these processing methodologies has to be demonstrated.

**Liquid Crystals.** In an effort to prepare monodomain films, the soft and self-organizing nature of liquid crystals have been

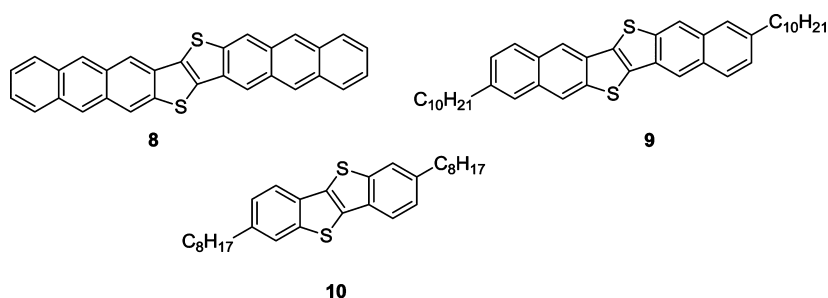


Figure 3. Chemical structure of high-mobility diacene-fused thieno[3,2-*b*]-thiophenes.

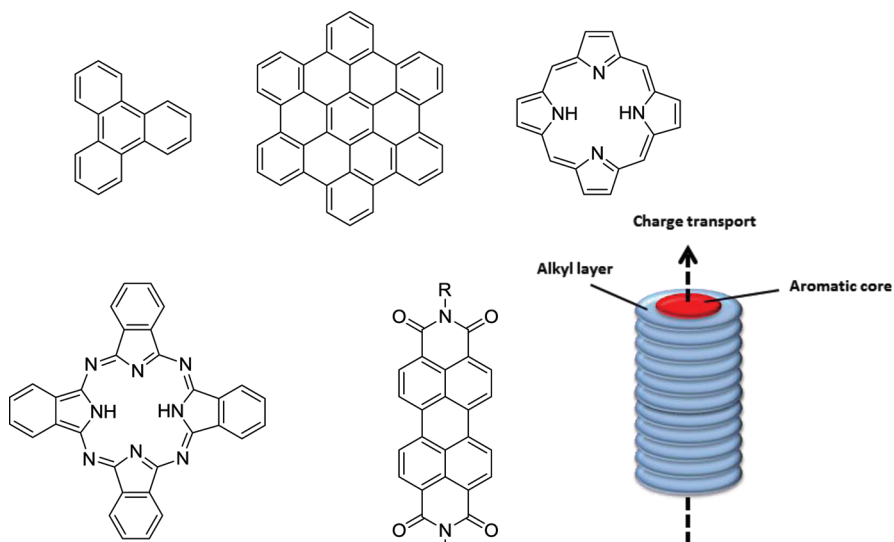


Figure 4. Aromatic cores of widely studied discotics and schematic representation of charge migration pathway in discotic liquid crystals.

envisaged as highly promising for easy-to-process high-mobility semiconductors. Liquid crystals can be easily aligned and solution/melt processed, and, more importantly, they have the ability to self-repair defects that act as traps for charge carriers.

Liquid crystalline mesophases are thermodynamically stable phases with a degree of order intermediate between the isotropic melt and crystalline solids that can be induced in some shape-anisotropic molecules by the action of temperature or solvents. In particular, discotic liquid crystals, usually composed by a rigid inner aromatic disk-like core (Figure 4) surrounded by a number of flexible chains linked to it, have been found to be promising materials for organic electronics. In the columnar mesophases characteristic of this type of materials, the disk-like molecules stack on top of one another, forming highly ordered columnar superstructures along which the  $\pi$ -orbital overlap between adjacent molecules favors the one-dimensional migration of charge carriers.

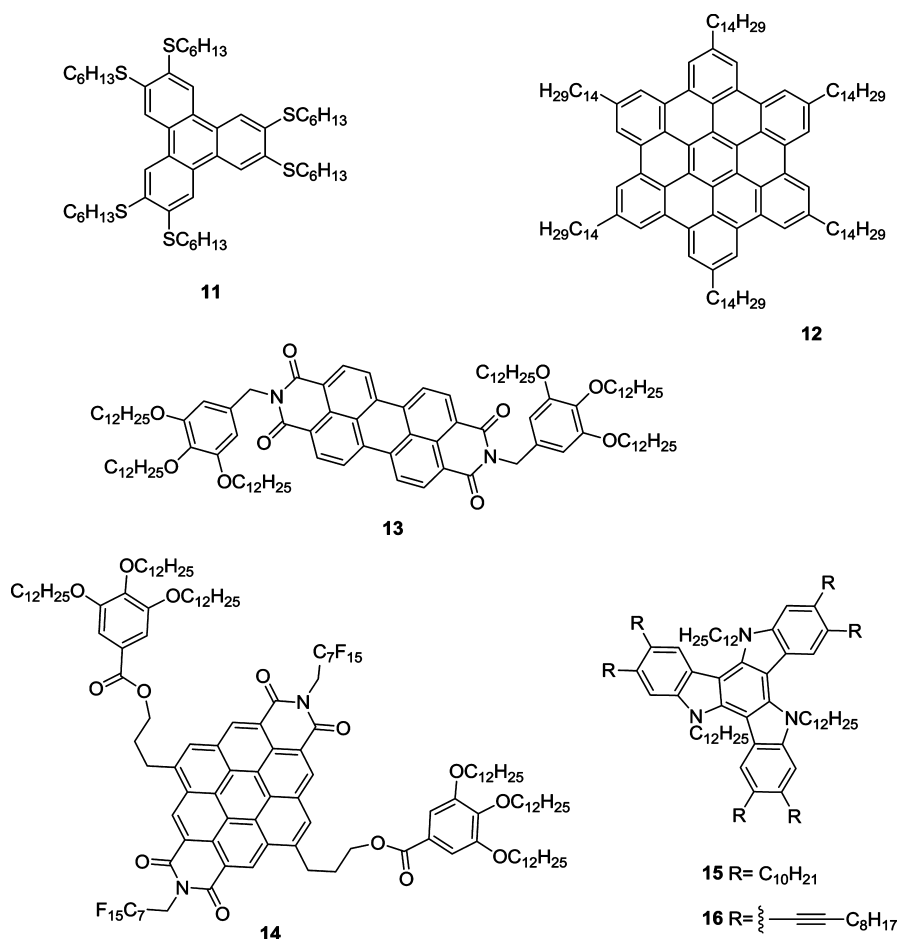
Early studies aimed to determine the semiconducting properties of discotic liquid crystals were performed on hexakis (hexylthio)triphenylene **11** (Figure 5), which presented a hole mobility to  $0.1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  in a three-dimensional helical columnar phase.<sup>22</sup> This high value motivated an enormous activity in the field directed to understanding and optimizing charge transport in discotic mesophases. The core, size, nature of chains, or connecting groups between the aromatic core and the flexible peripheral chains have been systematically varied in an attempt to establish clear design principles for high-performance semiconductors.

One of the factors that affect the mobility more is the size of the central core, as it has a strong influence in the overlapping  $\pi$ -orbital area. Large polycyclic aromatic cores have emerged as promising high mobility liquid crystals like hexabenzocoronene **12** (Figure 5), which presents a mobility of  $0.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  in the liquid crystalline phases that increases to  $1.1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  upon crystallization.<sup>23</sup> The relative local molecular orientation and intermolecular separation of neighboring aromatic cores within the stacks also have an important influence in the transfer integral and hence in the charge transport, as has been extensively discussed at both experimental and theoretical levels.<sup>24,25</sup>

In spite of the promising initial results obtained on triphenylene and the large activity in this area, surpassing the limit  $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  in the mesophases for hole semiconductors has proven to be a difficult task. Higher mobilities could be found, however, for n-type semiconducting discotic liquid crystals. Marder et al. found that 3,4,9,10-perylenediimide **13** (Figure 5) displays a charge-carrier mobility of  $1.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  in its disordered columnar hexagonal phase at room temperature.<sup>26</sup> Even higher values ( $6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ) were found for closely related columnar discotic 2,3:8,9-tetracarboxydiimide substituted with perfluorooctyl chains **14** (Figure 5).<sup>27</sup> In spite of this impressive high mobility, authors do not anticipate potential applications for this compound due to its extreme instability.

The reason for the difficulties in obtaining high mobilities in liquid crystals can be found in the fluctuation of the molecules within the stacks, which confers liquid crystals their interesting





**Figure 5.** Chemical structure of discotic liquid crystalline semiconductors.

self-healing properties but is also responsible of a certain intrastack dynamism, reducing carrier mobility in the bulk.<sup>28</sup> The preferred strategy for improving mobility in discotic mesophases has been the enhancement of the intermolecular order within the stacks by locking translation and rotation by bulky groups or introducing groups able to establish strongly directional interactions.

We have recently introduced heptacyclic 10,15-dihydro-5H-diindolo[3,2-a:3',2'-c]carbazole (triindole), as a central core for the construction of discotic liquids. Attachment of six decyl peripheral chains successfully induces columnar mesomorphism in this discotic core. Although no stacking periodicity was observed, **15** (Figure 5) has been found to exhibit a modest hole mobility  $\mu = 0.02 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  in the mesophases, highlighting the favorable intrinsic properties of the core.<sup>29</sup> In an attempt to raise the mobility values by increasing intracolumnar order, we have investigated different spacers to distance the peripheral alkyl chains from the central aromatic ring. Alkyne linkers have proved to efficiently increase the supramolecular order in the discotic mesophases while maintaining a reasonable distance between molecules in the stack, resulting in the discotic liquid crystalline material **16** with the highest hole mobility reported to date  $\mu \sim 1.4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . This result is particularly relevant since the intermolecular distance within the stacks (3.9 Å) is far from usual  $\pi$ - $\pi$  stacking, highlighting the importance of triindole as a core for high mobility columnar phases.<sup>30</sup>

Due to their characteristic structure (active conducting core, surrounded by an isolating cover), conduction in these materials is highly anisotropic, and contacts among aromatic units of different columns are hampered by the mantle of soft alkyl chains. A precise control of the aromatic cores on the substrate is therefore imperative to obtain optimal charge transport in the desired direction since orientation of the molecules will determine the direction of charge migration.

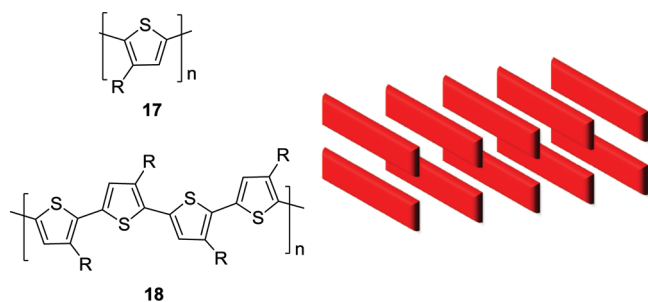
Disk-shaped molecules can be forced to orientate with columns parallel to the substrate (planar uniaxial alignment), as required for FETs or with columnar axis perpendicular to the substrate (homeotropic alignment) as needed for OLEDs or solar cells. Unfortunately, increasing the intercolumnar order leads to enhanced mobilities but significantly lowers the viscosity of the mesophases, making it more difficult to align the material. Orientation has been successfully achieved in many cases by different physical methods, but solutions found to this problem vary from material to material. At this stage, the controlled alignment of columns represents a major challenge for the practical application of high-mobility discotic liquid crystals.

It has been recently shown that different extended columnar assemblies of  $\pi$ -conjugated molecules bearing amide-appended chains can be aligned by the action of an electric field. The mechanism operating is proposed to involve unidirectional orientation of the amide linkers causing a macroscopic dipole, which can be oriented antiparallel to the applied electric field. An unprecedented long-range homeotropic columnar orientation

could be achieved, even in a 500  $\mu\text{m}$ -thick film.<sup>31</sup> While this behavior has been previously observed in other discotic liquid crystals,<sup>32</sup> the generality of the observation presented in this recent work holds a great promise for overcoming the problems of alignment on discotic liquid crystals necessary to develop practical applications of these materials.<sup>31</sup>

**Polymeric Materials.** Soluble polymeric semiconductors provide the desired ready processability needed for fast inkjet printing processes and roll-to-roll techniques required for the massive production of low-cost electronics. However, mobility values in polymeric semiconductors have traditionally remained behind crystalline semiconductors due to their inherent disorder.

As for conducting polymers, we focus our attention on polythiophenes **17** (Figure 6) as the representative, most



**Figure 6.** Chemical structure of polythiophenes and schematic representation of ordered lamellar domains.

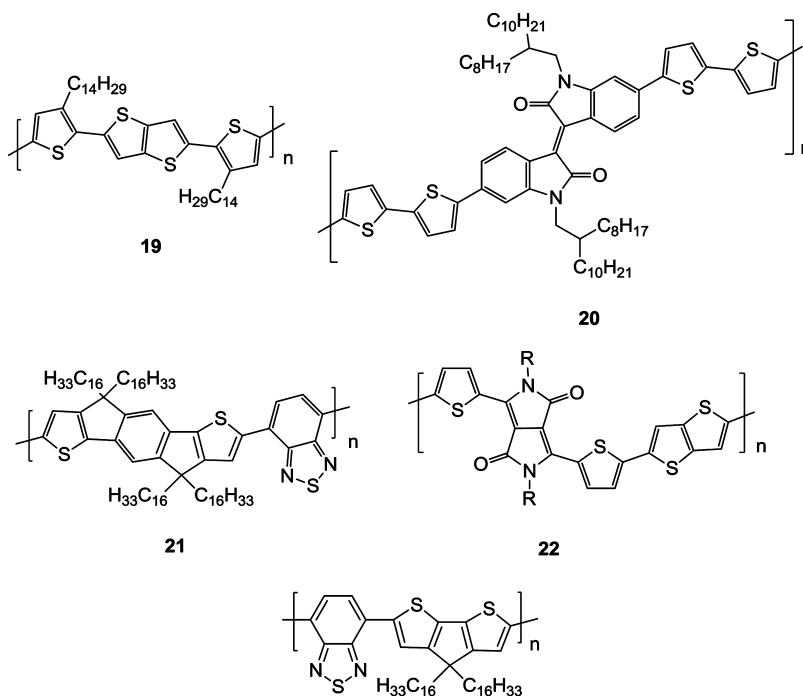
widely studied class of compounds. Polythiophenes usually form amorphous films with mobilities below  $10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  resulting from the absence of long-range structural order.

Higher mobilities (around  $0.1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ) have been found on regioregular poly(3-alkylthiophenes) **18** (Figure 6),<sup>33</sup> the most studied polymeric semiconductors. In these materials, the strong interaction between regularly oriented alkyl side chains leads to a two-dimensional lamellar structure in which the thienyl moieties are held in a close distance in a coplanar fashion (Figure 6). Mobility varies as a function of the degree of regioregularity, molecular weight, and deposition conditions and is highly dependent on the orientation of the ordered lamellar domains.

Attempts to increase the crystallinity have been performed by introducing more rigid units like thieno[3,2-*b*]thiophene moieties into the polythiophene backbone in order to reduce the conformational freedom. Upon annealing at the liquid crystalline phase and subsequent cooling, copolymer **19** (Figure 7) crystallizes, forming highly ordered domains that render mobility values as high as  $0.7 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ .<sup>34</sup>

Design strategies to improve charge carrier mobility of polythiophenes include the incorporation of electron deficient aromatic rings into the backbone. Attaching electron-withdrawing moieties lowers the HOMO level, which improves the air stability of these polymers (an important drawback of polythiophenes). It has been also reasoned that donor–acceptor interactions may help to closely pack the polymer chains resulting in enhanced mobilities. Mobilities up to  $0.79 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  have been found in air-stable isoindigo-based conjugated polymer **20** (Figure 7).<sup>35</sup>

This strategy has been extensively exploited using different donor and acceptor moieties such as copolymers **21** and **22** (Figure 7) reaching mobility values around  $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ .<sup>36,37</sup> Following this concept, Müllen et al. have recently reported a polymeric semiconductor **23** (Figure 7) that consists of the alternating arrangement of cyclopentadithiophene as a donor



**Figure 7.** High mobility polymeric semiconductors.

and a benzothiadiazole as an acceptor unit. The planar conjugated backbone ensures a close  $\pi$ -stacking of neighboring polymer chains. In this particular case, long-range macroscopic order and hole mobility increases with the number average molecular weight, ( $M_n$ ) leading to a mobility value of  $3.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  for the highest  $M_n$  ( $35 \text{ Kg mol}^{-1}$ ).<sup>38</sup>

Polymers are very appealing in terms of processability, but they pose problems of reproducibility due to variations in molecular weight, and polydispersity, from batch to batch. In addition, as it has been shown that crystallinity is also a key factor in polymeric materials and in best examples anisotropic transport is observed, requiring a precise control of the material organization and alignment to achieve optimal mobilities and complicating device fabrication. Low-molecular weight oligomers have been identified as attractive targets to substitute the usual polymeric materials in electro-active devices to avoid the classical view of polymers as high molecular weight macromolecules, poorly defined in terms of morphology and molecular weight.<sup>39</sup>

**Summary and Outlook.** While preliminary high-mobility molecular semiconductors have been identified mainly by trial and error, during the past decade, clear strategies have been established to design high-performance candidates, both at the molecular and supramolecular level. Concerning the strictly electronic aspect, extended aromatic systems offer a high amount of “mobile”  $\pi$ -electrons, while the incorporation of heterocyclic subunits (polithiophenes, pyrroles, etc.) into the polycyclic aromatic scaffold provides a rich electrochemical behavior. As for the supramolecular arrangement, the usually flat aromatic core structure tends to favor intermolecular stacking, and thus determines the mobility of the bulk material. In order to compensate undesired molecular packing, or precisely bias this effect, bulky substituents or structurally flexible moieties can be deliberately chosen. The presence of long alkyl side groups is another common structural feature: they increase the solubility, facilitating the processability, and may tune the crystalline/liquid crystalline properties of the resulting material.

While the function of each structural element is well understood, the assembly of the desired moieties into a molecular (and in turn, in a supramolecular arrangement) requires a considerable synthetic effort, and does not always lead to the expected emergent function. However, efforts directed to gain a better understanding of the interplay structure–performance will be useful to guide future material design toward the next generation of semiconductors. Organic

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materials present an unlimited variety in design and functionality, but, curiously, research on organic semiconductors has been performed on a narrow choice of molecules. New versatile candidates that are easy to functionalize will provide huge tailoring possibilities by using the power of organic synthesis. Creativeness and innovation are definitively necessary to develop new materials with the molecular and supra-

molecular complexity necessary to fulfill the different device requirements.

At this stage, the critical trade-off between performance and processability has not yet been successfully accomplished. Approaching the problem by exploiting the best characteristics of different classes of materials may offer promising results; e.g., the stepwise structural relaxation from high viscous liquid crystalline phases to the crystal is beneficial for fabricating uniform thin polycrystalline films, or high-mobility small semiconductors may be blended with semiconducting or inert polymers that provide easy processability and film uniformity.

As shown in this Perspective, continuous improvements in charge mobilities are being reported through the development of new semiconductors and optimization of materials processing, and this is possible thanks to an increasingly better understanding of factors affecting charge mobility. While

While materials with high enough mobilities for current applications have been developed, progressing from laboratory into a reliable and large-area manufacturing process is proving challenging.

materials with high enough mobilities for current applications have been developed, progressing from laboratory into a reliable and large-area manufacturing process is proving challenging. There is a clear need of efficient candidates that meet the requirement necessary for the high throughput development of devices; however, if we observe most recent advances, with many roadblocks being removed, we have reasons to be highly optimistic. The race toward the development of the organic semiconductor of the future is heating up.

## AUTHOR INFORMATION

### Corresponding Author

\*E-mail: bgl@icmm.csic.es; Phone: (+34) 91-3349031; Fax: (+34) 91-3720623.

### Notes

The authors declare no competing financial interest.

### Biographies

**Constanza Ruiz** graduated with a degree in Chemistry from the University of La Laguna (Spain). Currently, she is a Ph.D. student at the Instituto de Ciencia de Materiales de Madrid (ICMM), Spanish National Research Council (CSIC). Her research focuses on the synthesis of organic semiconductors for the preparation of devices.

**Eva M. García-Frutos** is a Tenured-Scientist in the ICMM (CSIC). She obtained her Ph.D. in Chemistry from the Universidad Autonoma de Madrid (UAM). After a postdoctoral stay at the Colorado State University and at the ICMM, she got a tenured position at the Instituto de Ciencia de Materiales de Aragon (ICMA). In 2012, she moved to ICMM. Her research focuses on the synthesis of semiconducting liquid crystals.

**Gunther Hennrich** graduated with a degree in Chemistry from the Universität Regensburg and obtained his Ph.D. from the TU Berlin, Germany. After a two-year postdoctoral stay at the University of Texas at Austin, he joined the UAM as a Ramón y Cajal Research Fellow. In 2008, he was appointed Assistant Professor, and in 2010 Associate



Prof. at the same university. His research focuses in the design and synthesis of functional organic molecules and their application as electro-optical materials.

**Berta Gómez-Lor** is a senior scientist in ICMM (CSIC). She obtained her Ph.D. from the University of Santiago de Compostela. She worked as a postdoctoral at Sandoz Pharma (Basel), at the University of Illinois, and at the UAM. In 2003, she obtained a position as a tenured scientist at the ICMM. Her research interest is the synthesis of new materials for application in organic electronics such as light-emitting diodes, photovoltaics, or thin film transistors. For further details, see <http://www.icmm.csic.es/oeg/>

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