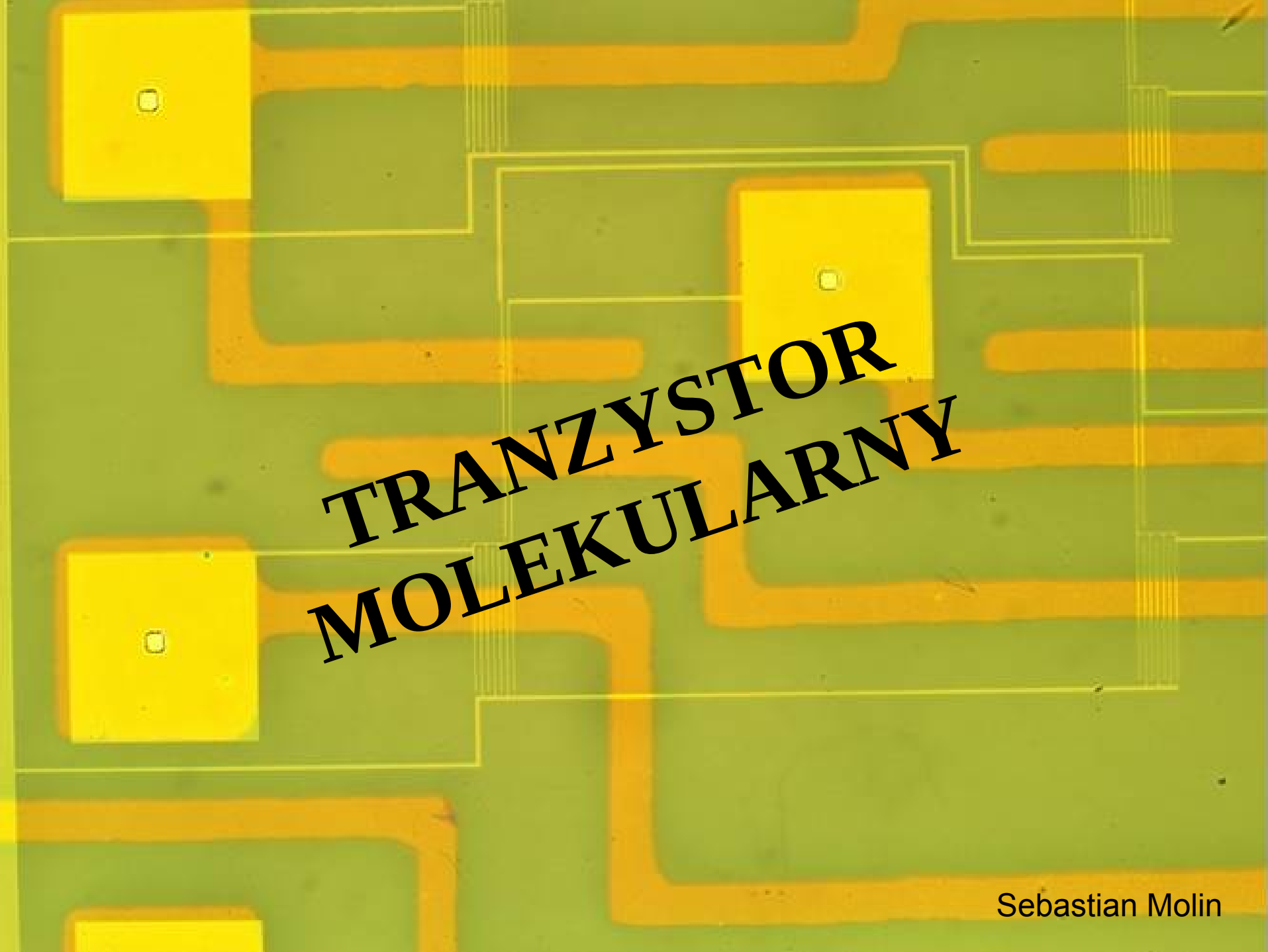


The background of the slide is a high-magnification scanning electron micrograph (SEM) of a molecular transistor. It shows a complex network of thin, yellowish-gold conductive lines on a dark green substrate. Several larger, rectangular yellow pads are visible, which serve as electrical contacts for the molecular components. The overall pattern is intricate, with lines branching and connecting different parts of the device.

TRANZYSTOR MOLEKULARNY

Sebastian Molin

Plan seminarium:

- Krótki wstęp
- Czym jest tranzystor??
- Materiały organiczne
- Budowa OTFT
- Wytwarzanie

THE HIDDEN BIOSPHERE: Is There Life Beneath the Ocean Floor?

SCIENTIFIC AMERICAN

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THE BIRTH OF MOLECULAR ELECTRONICS

DWARF GALAXIES
AND STARBURSTS

THE NETWORK
INSIDE A CELL

SPECIAL REPORT:
THE NEW FACE OF
WAR

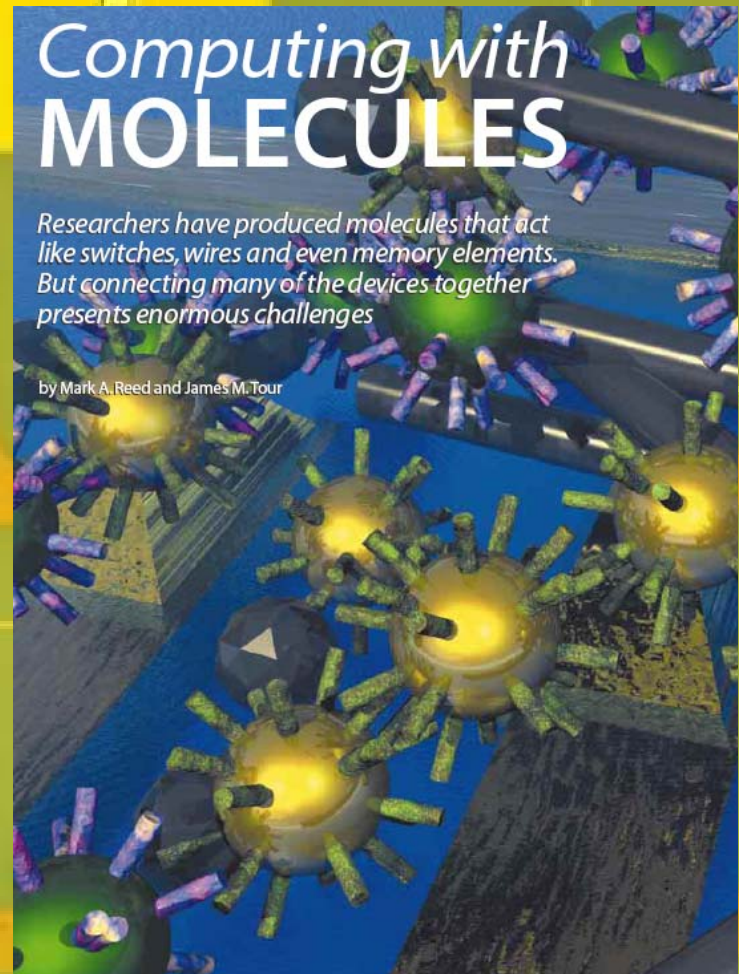
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Computing with MOLECULES

Researchers have produced molecules that act like switches, wires and even memory elements. But connecting many of the devices together presents enormous challenges

by Mark A. Reed and James M. Tour



BENZENEDITHIOL molecule, acting as a molecular conductor, was tested between gold tips in the geometry illustrated here. The molecule's current-voltage characteristics (*graph, below*) closely matched theoretical projections. The relatively large current flow bodes well for the ability of molecular devices to work with more conventional electronics.

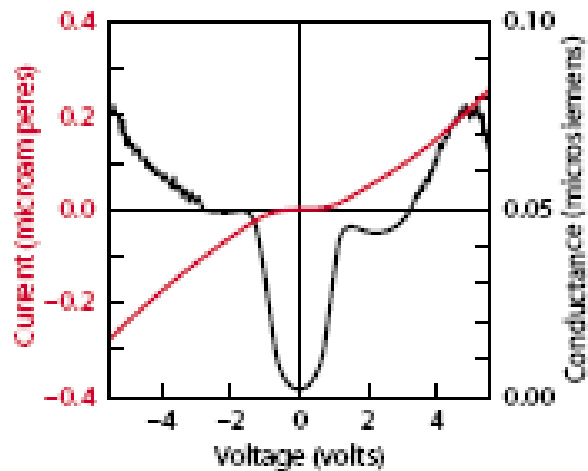




Figure 2. Flexible solar cell technology incorporated into a military tent

molekularnej:
luminescencyjne
(devices)

- C
 - S
 - C
- W
- zy
- cienkowarstwowe
Transistors)



OLED Display Screen (from Universal Display Corp)

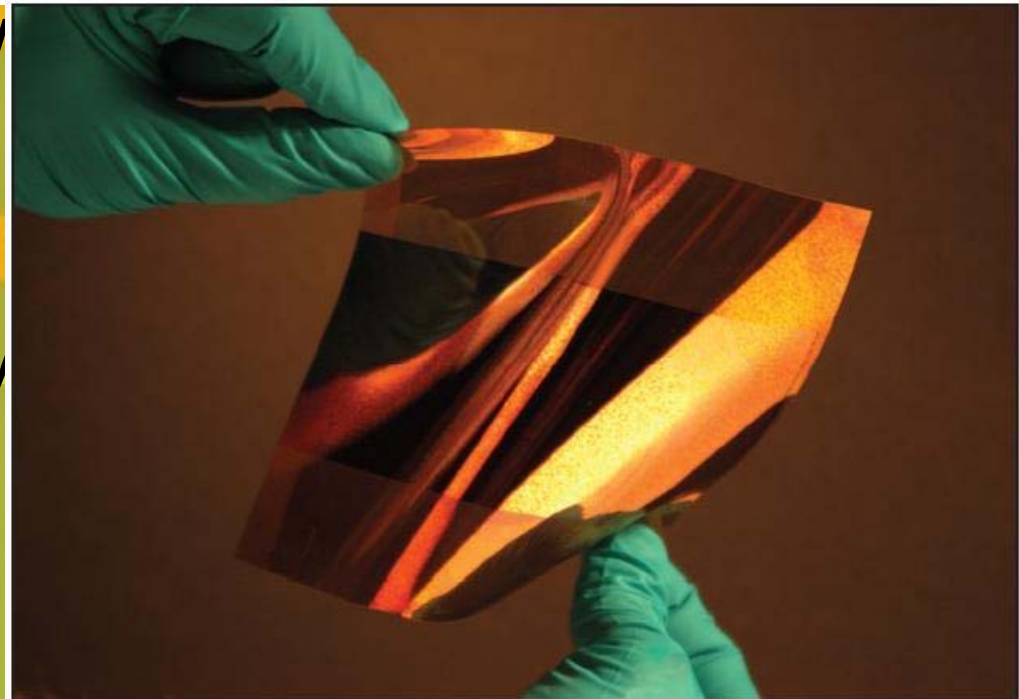
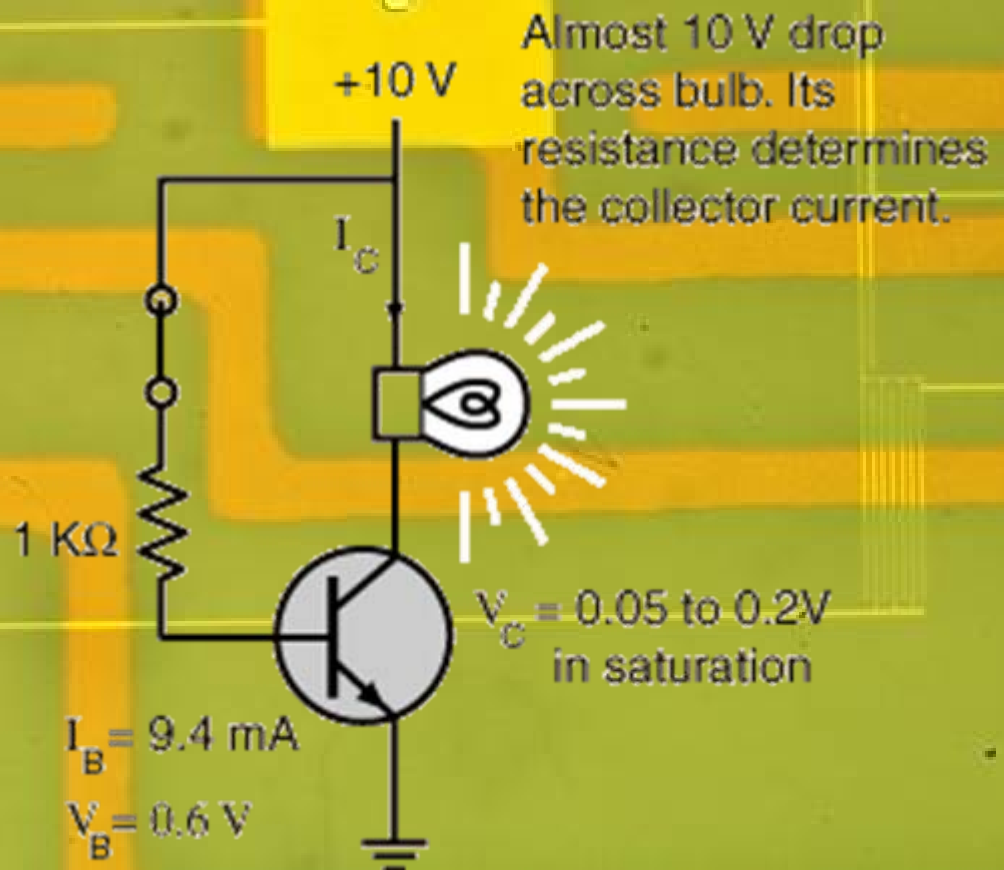
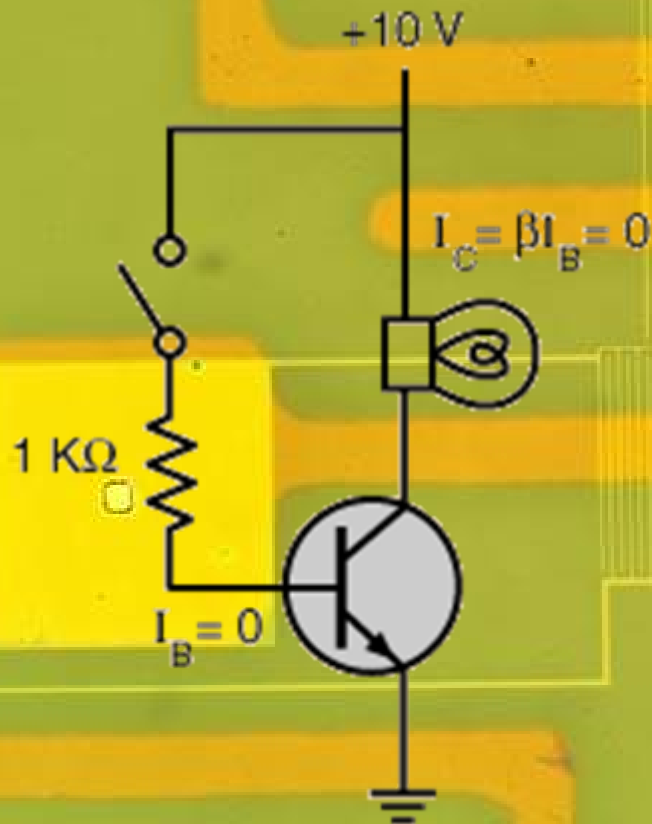


Figure 1. A flexible, organic-based solar cell

Po co nam tranzystory??

PRZEŁĄCZNIK I WZMACNIACZ

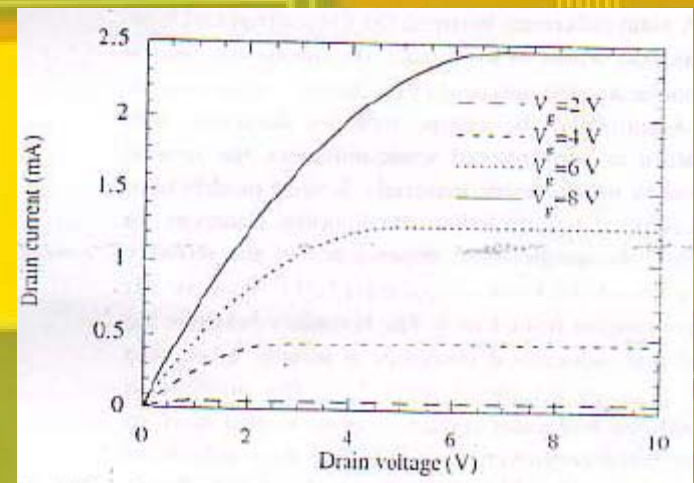
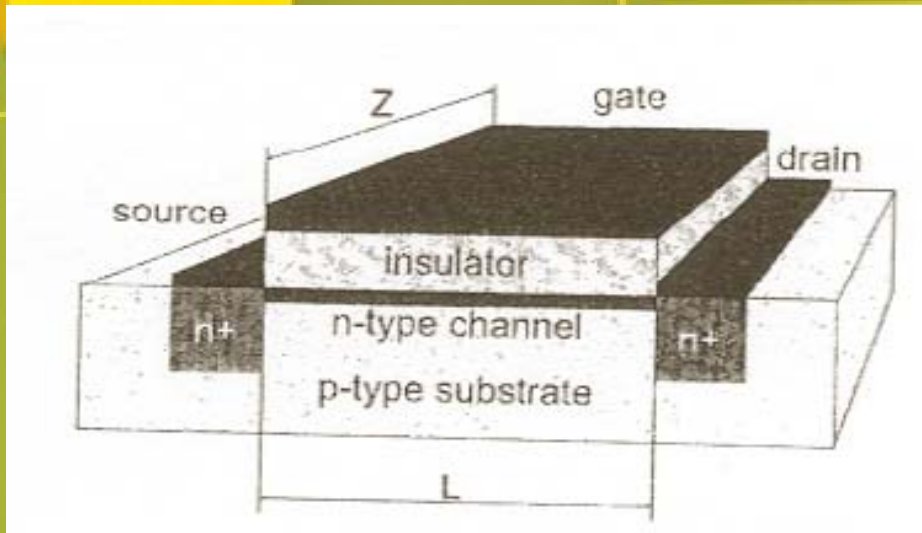


Tranzystory **Field-Effect Transistor:**

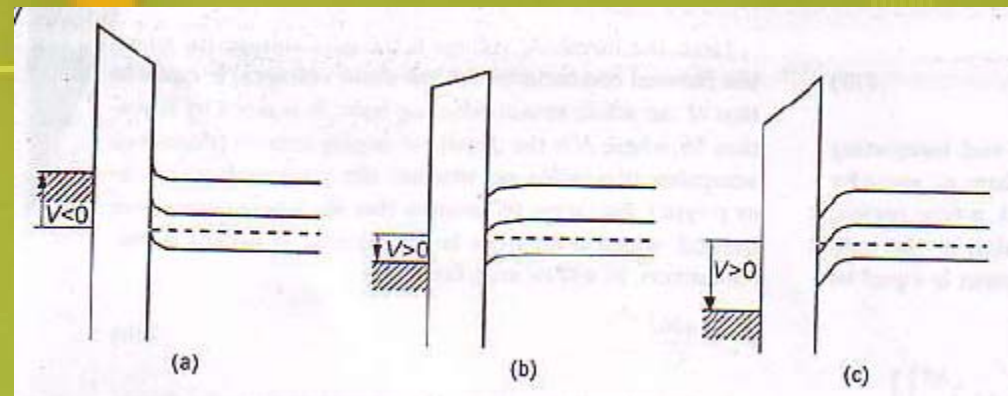
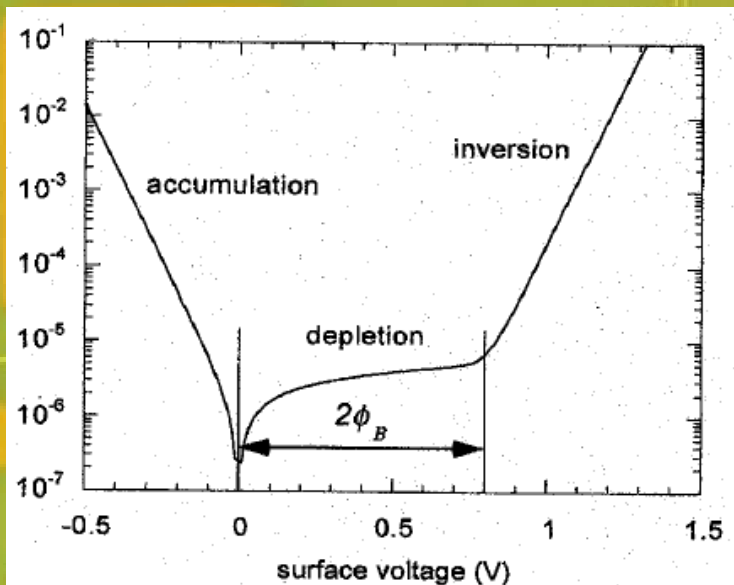
FET – tranzystory polowe - unipolarne, w których prąd wyjściowy jest funkcją napięcia

- **MISFET** – Metal Insulator Semiconductor
- **MESFET** – Metal Semiconductor
- **TFT** – Thin Film Transistor

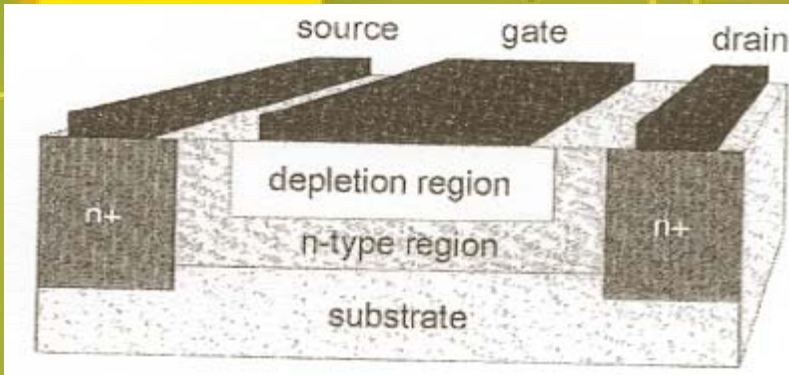
Tranzystor MISFET



$$I_d = \frac{Z}{L} \mu C_i \left\{ \left(V_g - 2\phi_b - \frac{V_d}{2} \right) V_d - \frac{2}{3} \frac{\sqrt{2\epsilon_s q N_a}}{C_i} \left[(V_d + 2\phi_b)^{3/2} - (2\phi_b)^{3/2} \right] \right\}$$



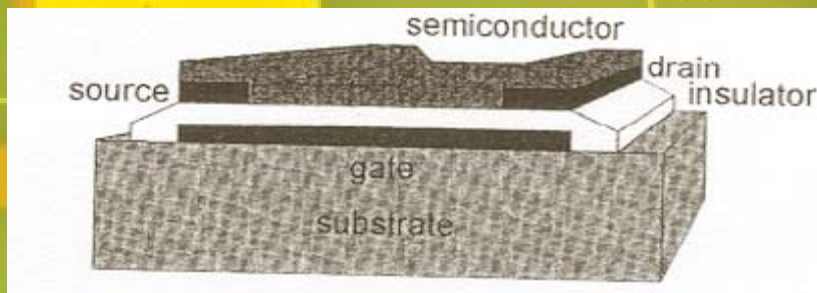
Tranzystor MESFET:



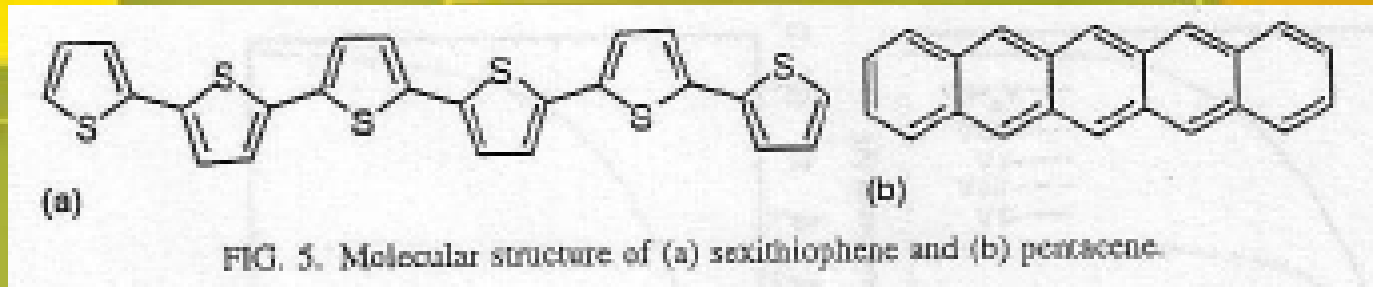
$$I_d = g_0 \left\{ V_d - \frac{2 \left[(V_d + V_{bi} - V_g)^{3/2} - (V_{bi} - V_g)^{3/2} \right]}{3 V_p^{1/2}} \right\}$$

Tranzystor TFT:

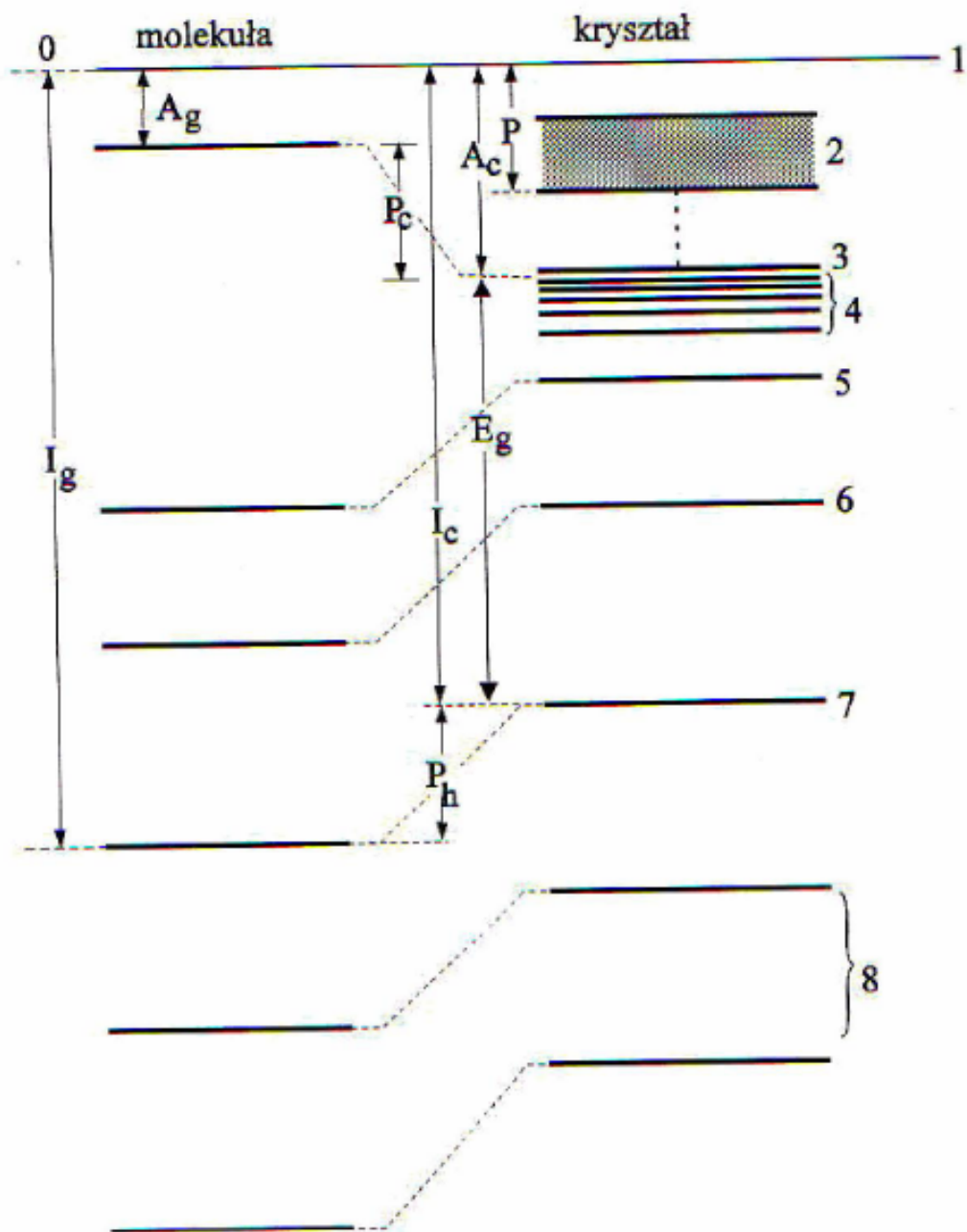
1962 – Weimer, nadaje się do materiałów o małej przewodności, aktualnie używane do a-Si:H, działa w zakresie akumulacji.



Materiały organiczne:



- Półprzewodniki organiczne znane od lat 40
- Pierwszy tranzystor organiczny w 1986 roku
- LUMO (pusty) & HOMO (pełny)



- 1 - poziom próżni (przyjęto $E=0$),
- 2 - najwyższe poziomy przewodnictwa,
- 3 - najniższy poziom przewodnictwa,
- 4 - stany CT,
- 5 - pierwszy stan wzbudzony singletowy,
- 6 - stan trypletowy,
- 7 - poziom walencyjny,
- 8 - głębsze poziomy walencyjne,

- A_g - energia powinowactwa,
 I_g - potencjał jonizacji cząsteczki,
 P_c - energia polaryzacji,
 A_c - energia powinowactwa kryształu,
 I_c - potencjał jonizacji kryształu,
 E_g - przerwa energetyczna,
 P_h - energia polaryzacji dziury,
 P - górne pasmo przewodnictwa

Rys.2.5. Poziomy energetyczne izolowanej molekuly i kryształu. Oznaczenia:

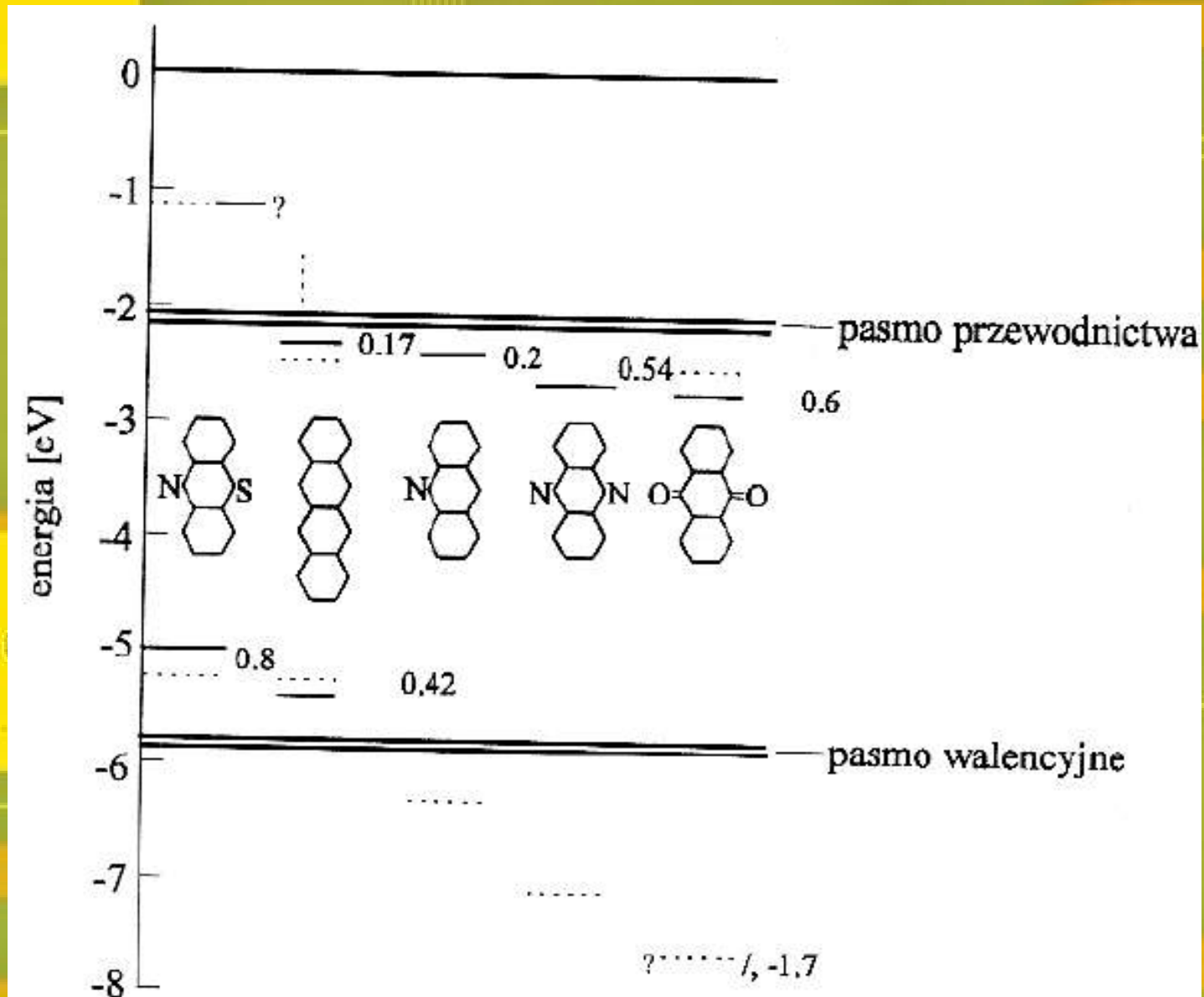
**Potencjały jonizacyjne oraz powinowactwa elektronowe
dla szeregu molekuł i kryształów**

Związki	I_g [eV]	A_g [eV]	I_c [eV]	E_g [eV]	$A_c=(I_c-E_g)$ [eV]
benzen	9.2	-1.4	-	~6	-
naftalen	8.2	-0.2	6.8	~5	~ 1.8
antracen	7.5	0.6	5.9	3.9	2.0
tetracen	7.0	1.1	5.4	3.1	2.4
pentacen	6.7	1.2	5.1	2.2	2.9
fenantren	8.0	0.2	6.5	-	-
piren	7.5	0.5	5.8	-	-
9,10 -dwo- bromoantracen	7.0	1.3	6.1	-	-
perylene	7.0	1.1	5.4	2.9	2.5

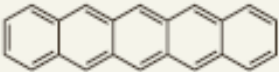
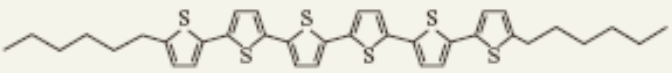
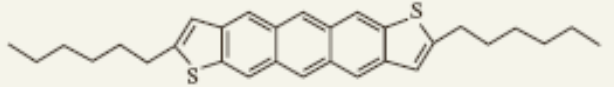
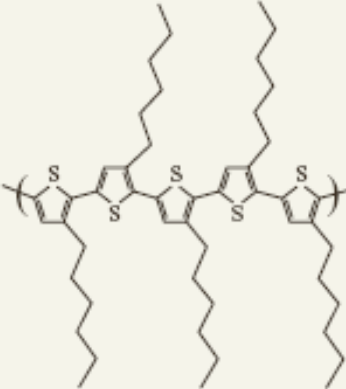
Obliczone i zmierzone wartości najmniejszej przerwy energetycznej
w kilku wybranych kryształach molekularnych

Kryształ	E_g (teoret.) [V]	E_g (dośw.) [eV]
naftalen	4.0	4.4
antracen	3.4	3.5
tetracen	3.0	2.7-2.9
pentacen		2.2
perylene		3.1-3.5
9,10-dwuchloroantracen		3.3

Poziomy energetyczne pułapek ładunku utworzone w antracenie przez wybrane domieszki :

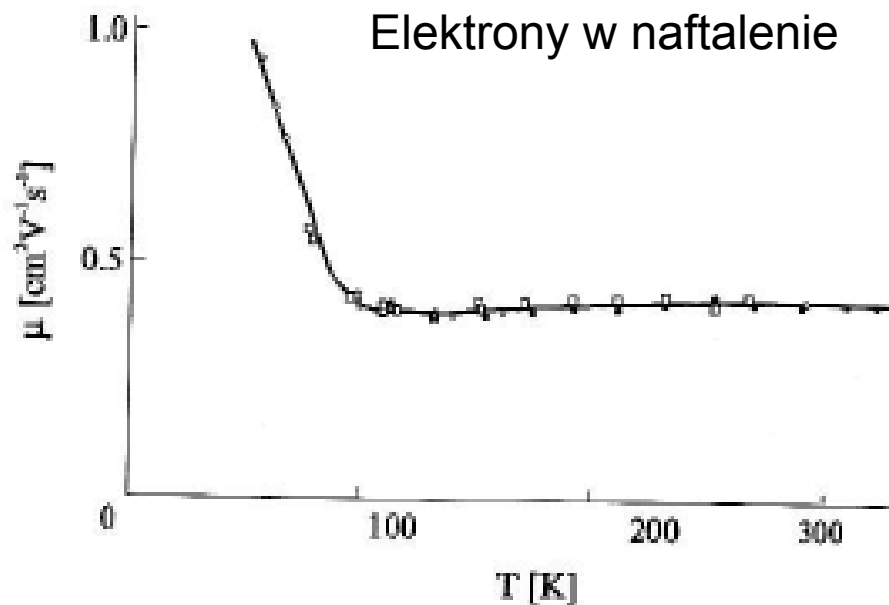


Ruchliwość nośników ładunku:

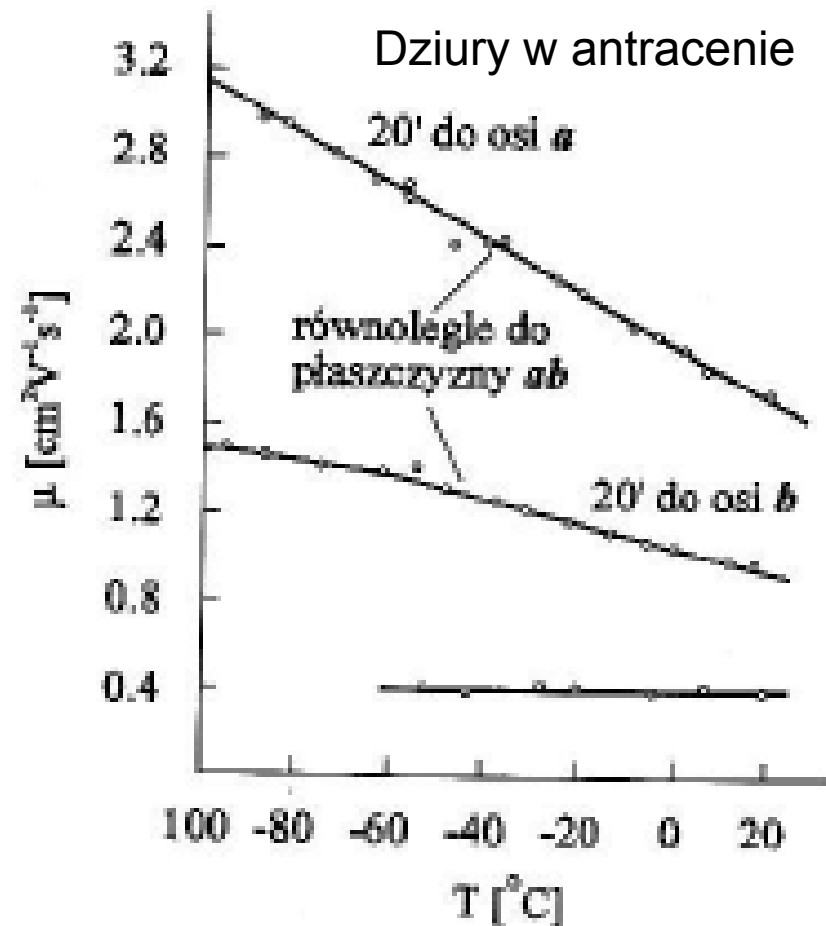
<i>Semiconductor</i>	<i>Representative chemical structure</i>	<i>Mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)</i>
Silicon	Silicon crystal	300–900
	Polysilicon	50–100
	Amorphous silicon	~1
Pentacene		~1
α,ω -dihexylsexithiophene		10^{-1}
α,ω -dihexylanthra-dithiophene		10^{-1}
Regioregular poly(3-hexylthiophene)		10^{-1}
Organic–inorganic hybrid	Phenethylamine–tin iodide	~1

Ruchliwość nośników ładunku:

Elektrony w naftalenie



Dziury w antracenie



Pomiar ruchliwości:

- Time-Of-Flight
- FET measurement

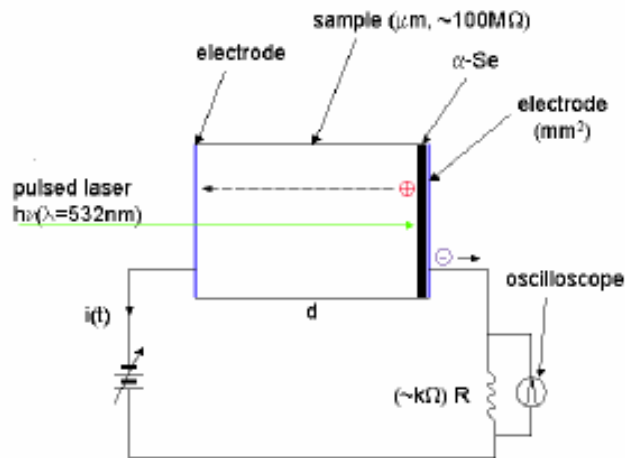
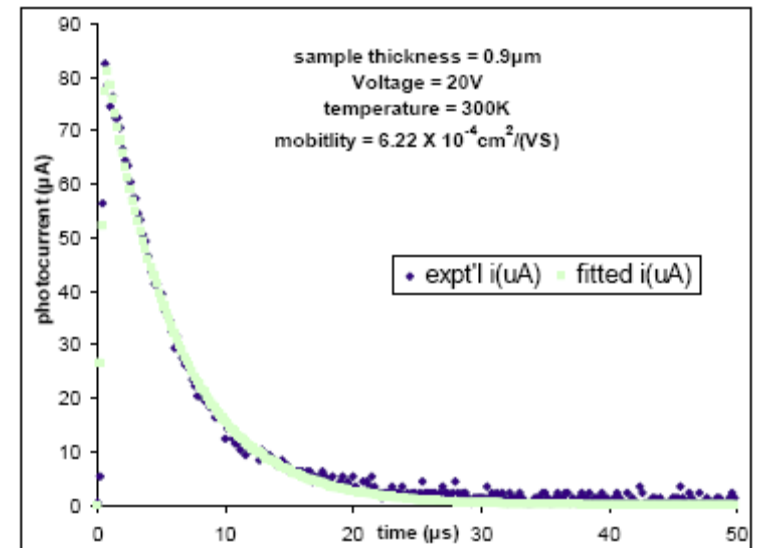


Figure 4.3 A typical experiment setup for measuring mobility using TOF.



Ruchliwość w pentacenie:

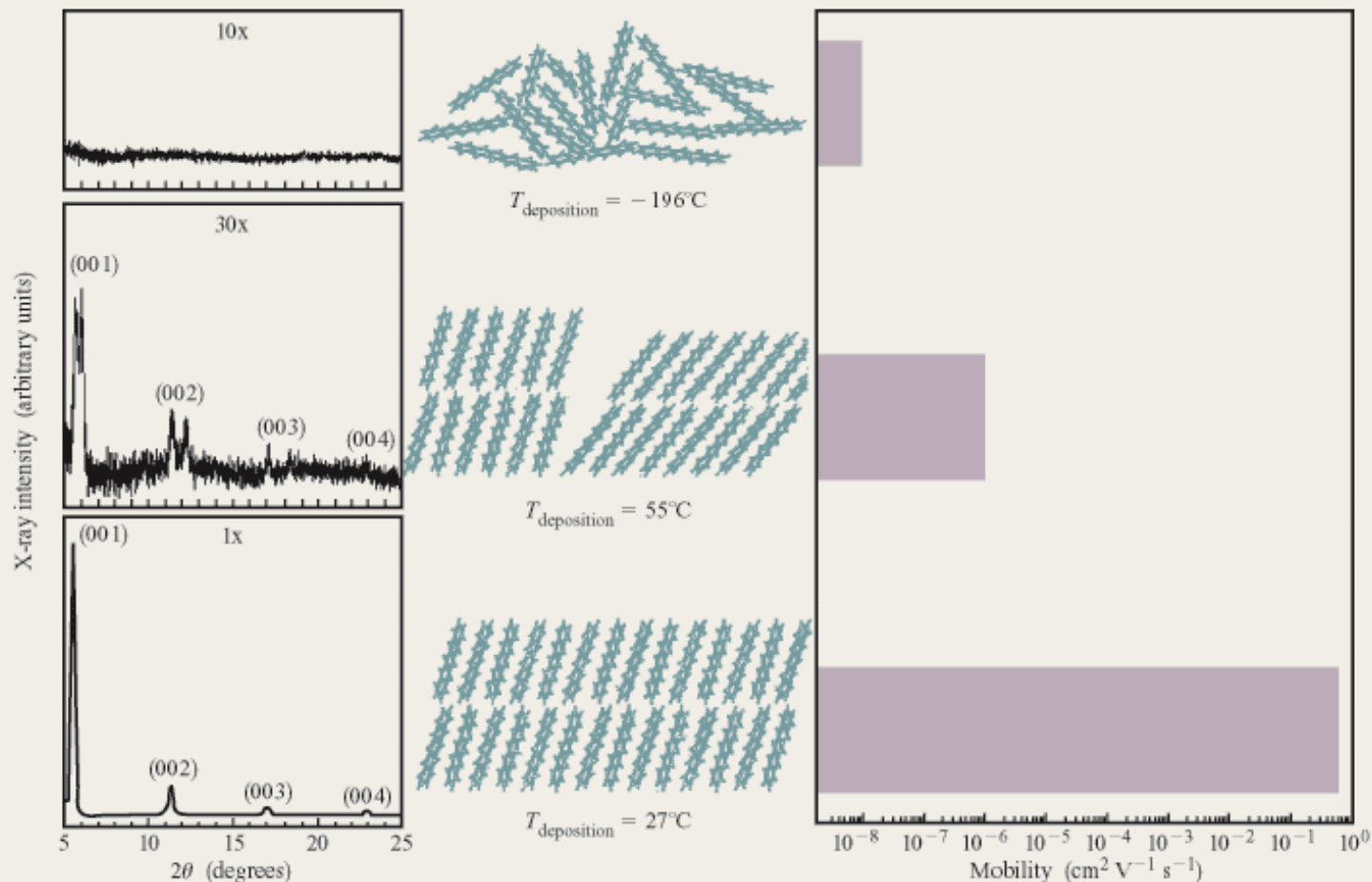


Figure 7

Comparison of X-ray diffraction patterns, schematic representations of structural order, and field-effect mobilities for three different phases of thin-film pentacene. An amorphous phase is achieved using a substrate temperature, $T_{\text{deposition}}$, of -196°C and a deposition rate DR of $0.5 \text{ \AA s}^{-1}$. A single phase results at the temperature $T_{\text{deposition}} = 27^{\circ}\text{C}$ and $DR = 1 \text{ \AA s}^{-1}$, while $T_{\text{deposition}} = 55^{\circ}\text{C}$ and $DR = 0.25 \text{ \AA s}^{-1}$ yields a double phase. Data partially taken from [28].

Organiczne półprzewodniki:

- Typy „p” i „n” nie pochodzą od domieszek
- Dwie koncepcje w organicznych:
 - Półprzewodnik organiczny jest typu „n” gdy wyróżniony jest transport elektronów, tzn. gdy ruchliwość elektronów jest dużo większa niż dziur (electron or hole transport materials)
 - Wstrzykiwanie ładunku: półprzewodnik typu „n” cechuje się łatwością wstrzykiwania elektronów czyli dużym powinowactwem elektronowym podczas gdy typu „p” ma mały potencjał jonizacji, łatwo oddaje elektrony

Organiczne półprzewodniki:

- Przewodnictwo typu „n” i typu „p”:

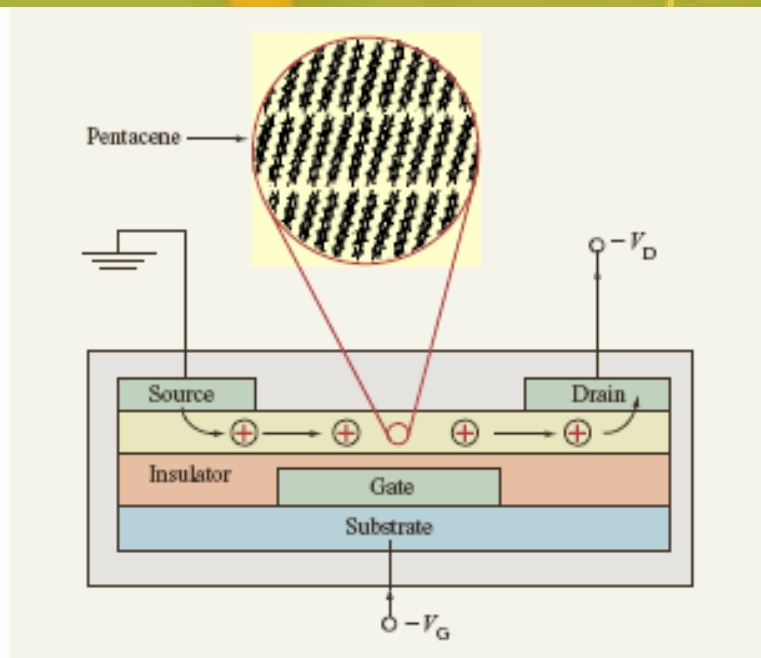


Figure 1

Schematic of organic semiconducting p-type thin-film transistor with top contacts.

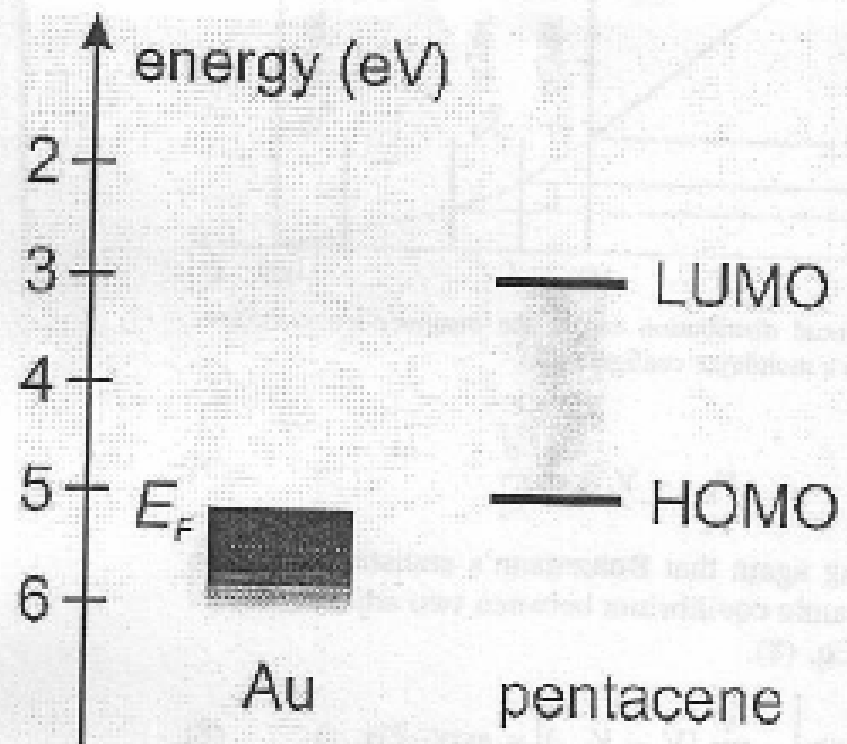
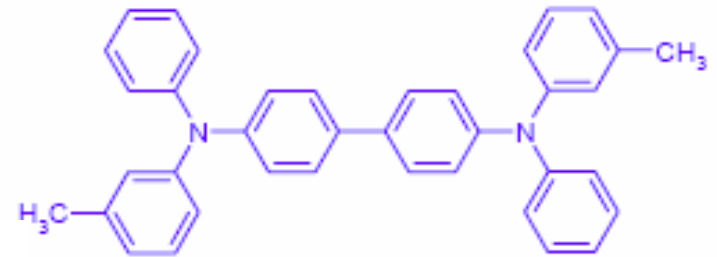


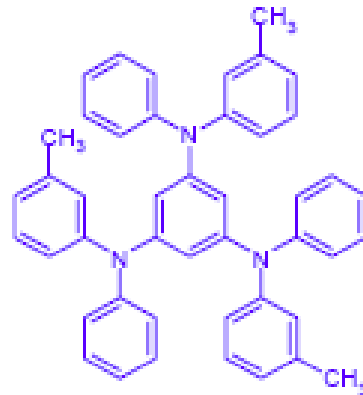
FIG. 3. This energy scheme compares the work function of gold to the energy of the frontier orbitals of pentacene. Data taken from Ref. 20.

Hole Transport Molecules

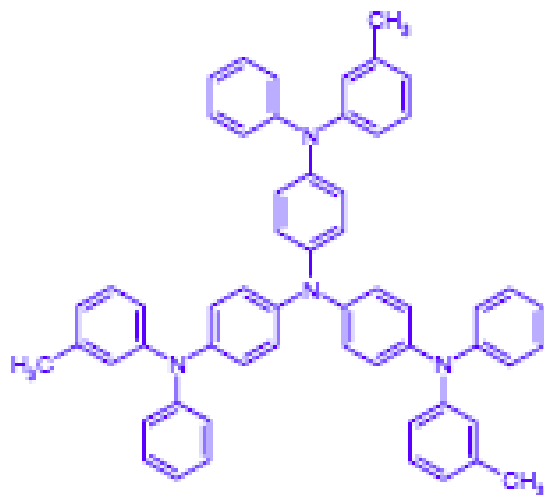
- N,N'-Bis(3-methylphenyl)-N,N'-diphenylbenzidine



- 1,3,5-Tris(3-methylphenyl)-N,N'-diphenylbenzidine



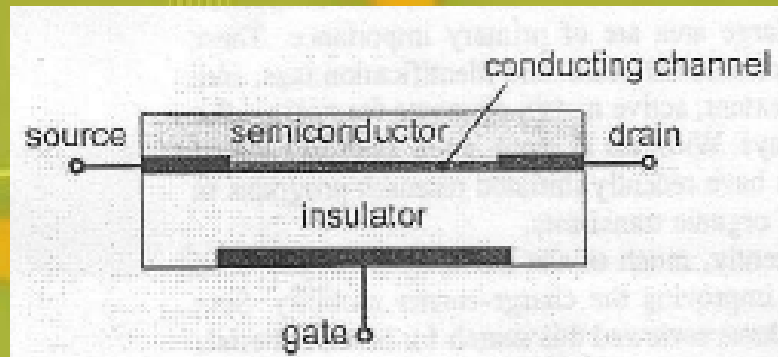
- 1,3,5-Tris(3-methylphenyl)-N,N'-diphenylbenzidine



- 1,3,5-Tris(3-methylphenyl)-N,N'-diphenylbenzidine

Budowa OTFT:

- Czynniki ważne do budowy OTFT:
 - Duża ruchliwość ładunków w kanale przewodzącym jako parametr podstawowy;
 - Małe opory ohmowe kontaktów pomiędzy drenem-kanalem-źródłem
 - Grubość kanału przewodzącego
 - Współczynnik on/off



Konfiguracja TFT a opór kontaktów:

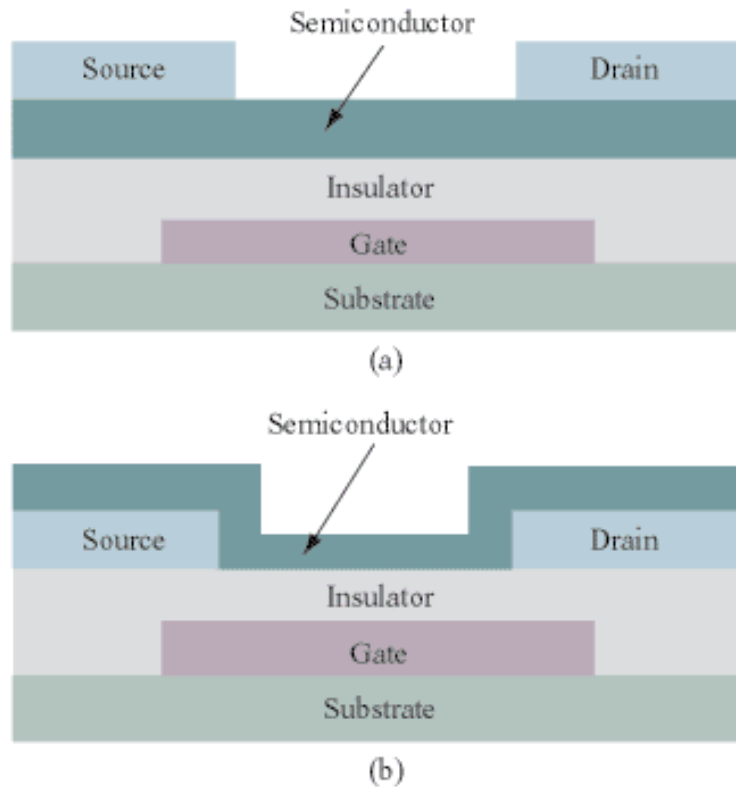


TABLE I. Contact resistance R_C extracted through characteristic modeling; TC, top contact; BC, bottom contact. In all cases, the contacts are made of gold.

TFT	Semiconductor	Gate width (μm)	R_C (ohm)	Normalized R_C ($\times \text{cm}$)	Reference
TC	Pentacene	220	1×10^5	2×10^3	32
BC	Pentacene	220	5×10^4	1×10^3	32
TC	Sexithiophene	1000	2×10^5	2×10^4	33

Figure 2

OTFT device configurations: (a) Top-contact device, with source and drain electrodes evaporated onto the organic semiconducting layer. (b) Bottom-contact device, with the organic semiconductor deposited onto prefabricated source and drain electrodes.

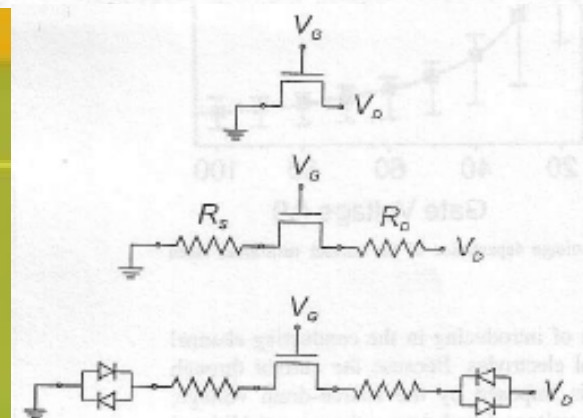
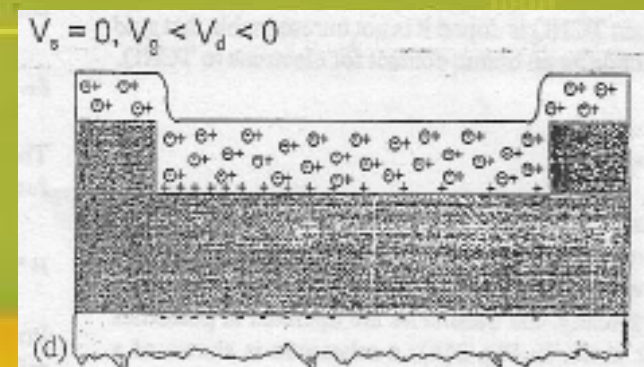
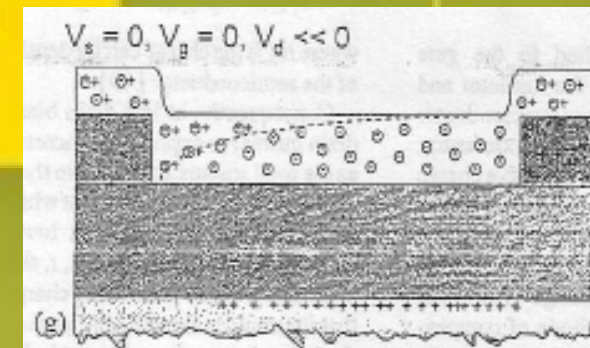
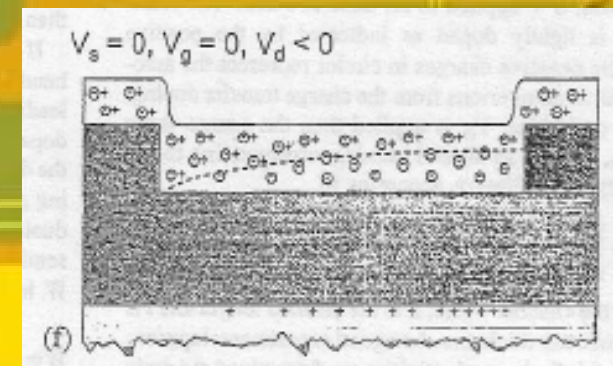


FIG. 8. Equivalent circuit of the TFT without (top) and with (middle) contact resistances. The bottom circuit includes diode to account for non-linearity in the contact resistance.

Współczynnik ON/OFF

- ON: $V_g = V_d < 0$
- OFF: $V_g = 0, V_d < 0$
- Stosunek prądu płynącego w stanie **ON** do prądu płynącego w stanie **OFF**



Współczynnik ON/OFF

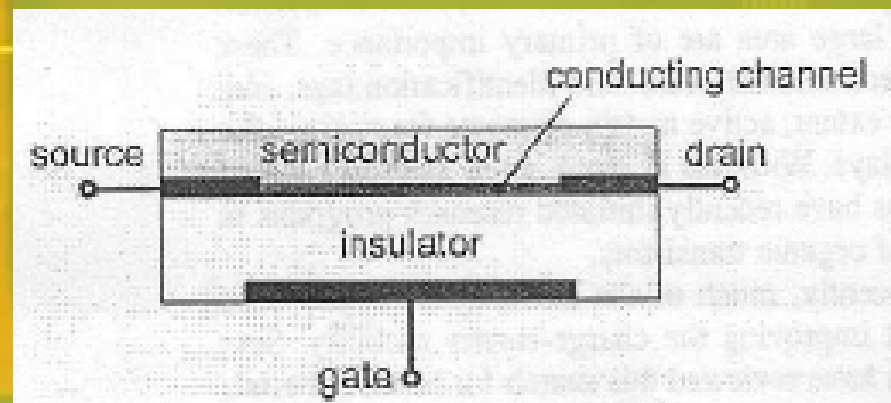
$$\frac{I_{on}}{I_{off}} = \frac{\frac{Z\mu C_i V_d^2}{2L} + \frac{\sigma Zt}{L} V_d}{\frac{Z\sigma q N_A t^2}{6LC_i} \left(1 + 3\frac{C_i}{C_d}\right)} = \frac{\frac{\mu C_i V_d^2}{2} + \sigma t V_d}{\frac{\sigma q N_A t^2}{6C_i} \left(1 + 3\frac{C_i}{C_d}\right)} \rightarrow \frac{I_{on}}{I_{off}} = \left(\frac{\mu}{\sigma}\right) \frac{C_i^2}{q N_A t^2} V_d^2$$

Zatem musimy stosować:

- Cienkie warstwy
- Izolatory o dużych pojemnościach powierzchniowych
- Materiały o dużym stosunku ruchliwości do przewodności

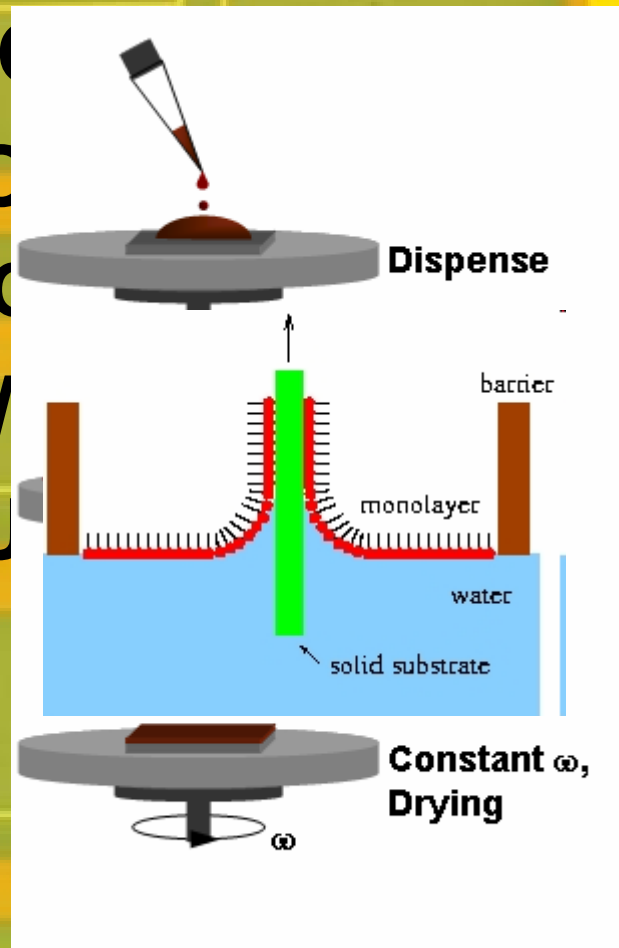
Wytwarzanie:

- „**inverted architecture**”: najpierw tworzymy „gate”, materiał półprzewodzący jako ostatni
- **Bramka** (gate) – wykonana z silnie domieszkowanego krzemu, na który nanoszona termicznie jest warstwa SiO_2
- **Źródło i dren** wykonane metodą klasycznej mikrolitografii



Nanoszenie półprzewodnika:

- ELECTROCHEMICAL DEPOSITION
- SOLUTION DEPOSITION
 - SPIN COATING
- VACUUM DEPOSITION
- LANGMUIR-BLODGETT



DEPOSITION

DEPOSITION

N

TECHNIQUE

Półprzewodnik w OFET:

- Tworzy praktycznie warstwę 2D
- Różny zależnie od procesu wytwarzania

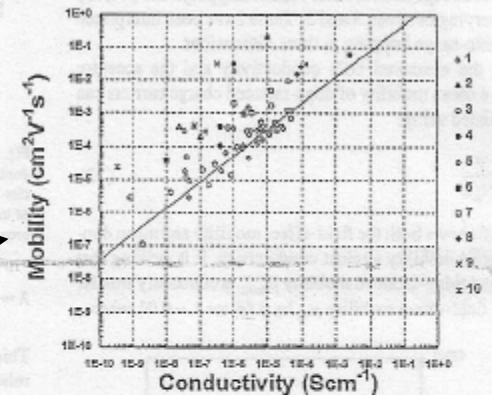


Fig. 12. Field-effect mobility plotted against bulk conductivity for a range of conjugated materials. Key for Fig. 12:

Data set	Material	Deposition technique	Reference
1	polythiophene	electrochemical	Kozuka et al. [9,19]
2	poly(thienylene vinylene)	precursor route	Pachigani et al. [48]
3	pentacene	precursor route	Brown et al. [27]
4	sexithiophene	vacuum deposition	Horowitz et al. [21,49]
5	poly(thienylene vinylene)	precursor route	this study
6	polycyclopentadiene	precursor route	Barroughs et al. [4]
7	pentacene	vacuum deposition	Horowitz et al. [50]
8	pentacene	precursor route	this study
9	sexithiophene	vacuum deposition	Dodabalapur et al. [20]
10	pentacene	vacuum deposition	Dimitrakopoulos et al. [51]

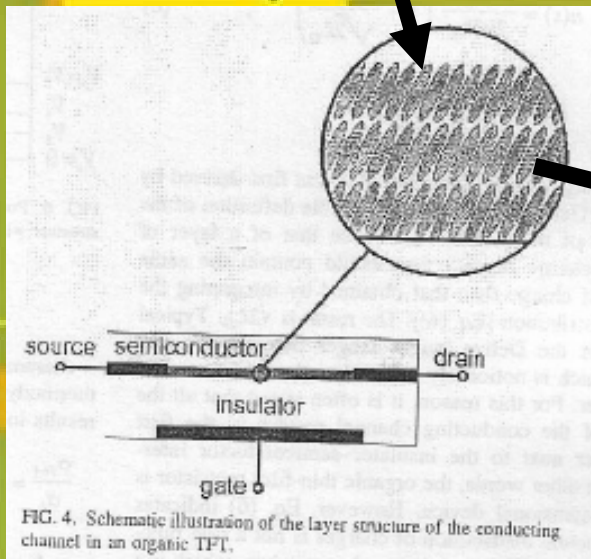


FIG. 4. Schematic illustration of the layer structure of the conducting channel in an organic TFT.

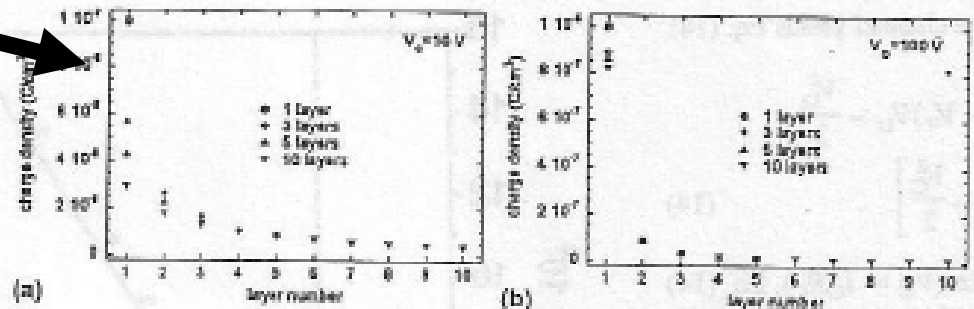


FIG. 7. Charge density in each layer for films of various thicknesses at a gate voltage of (a) 10 V and (b) 100 V.

Gotowy tranzystor:

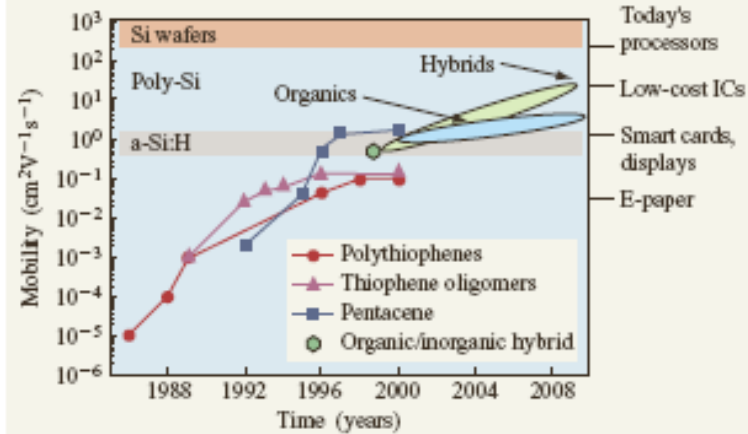


Figure 3

Performance of organic and hybrid semiconductors.

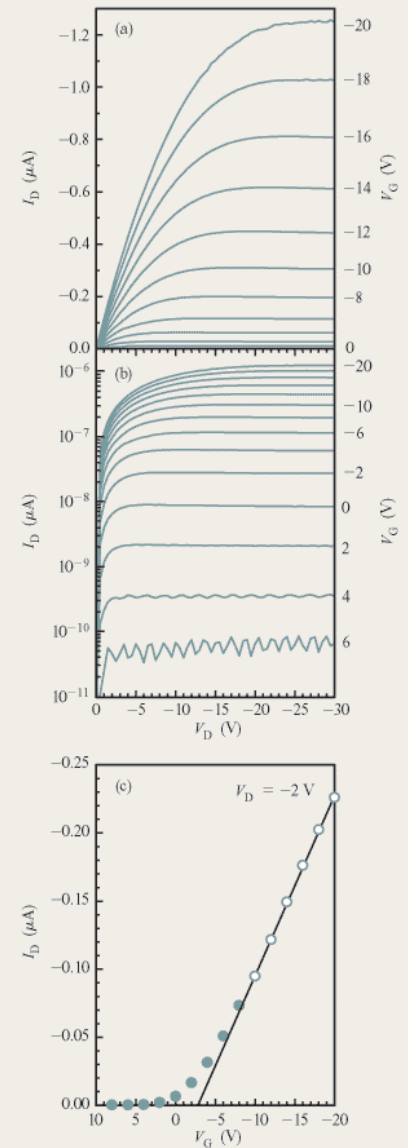
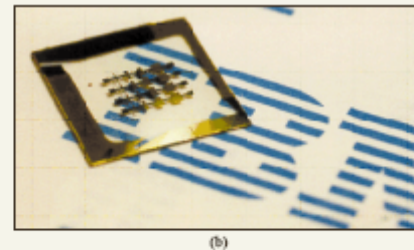
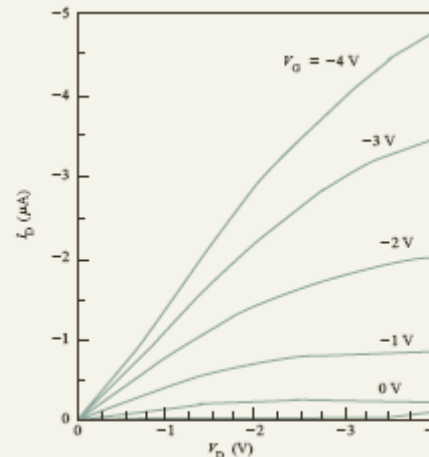
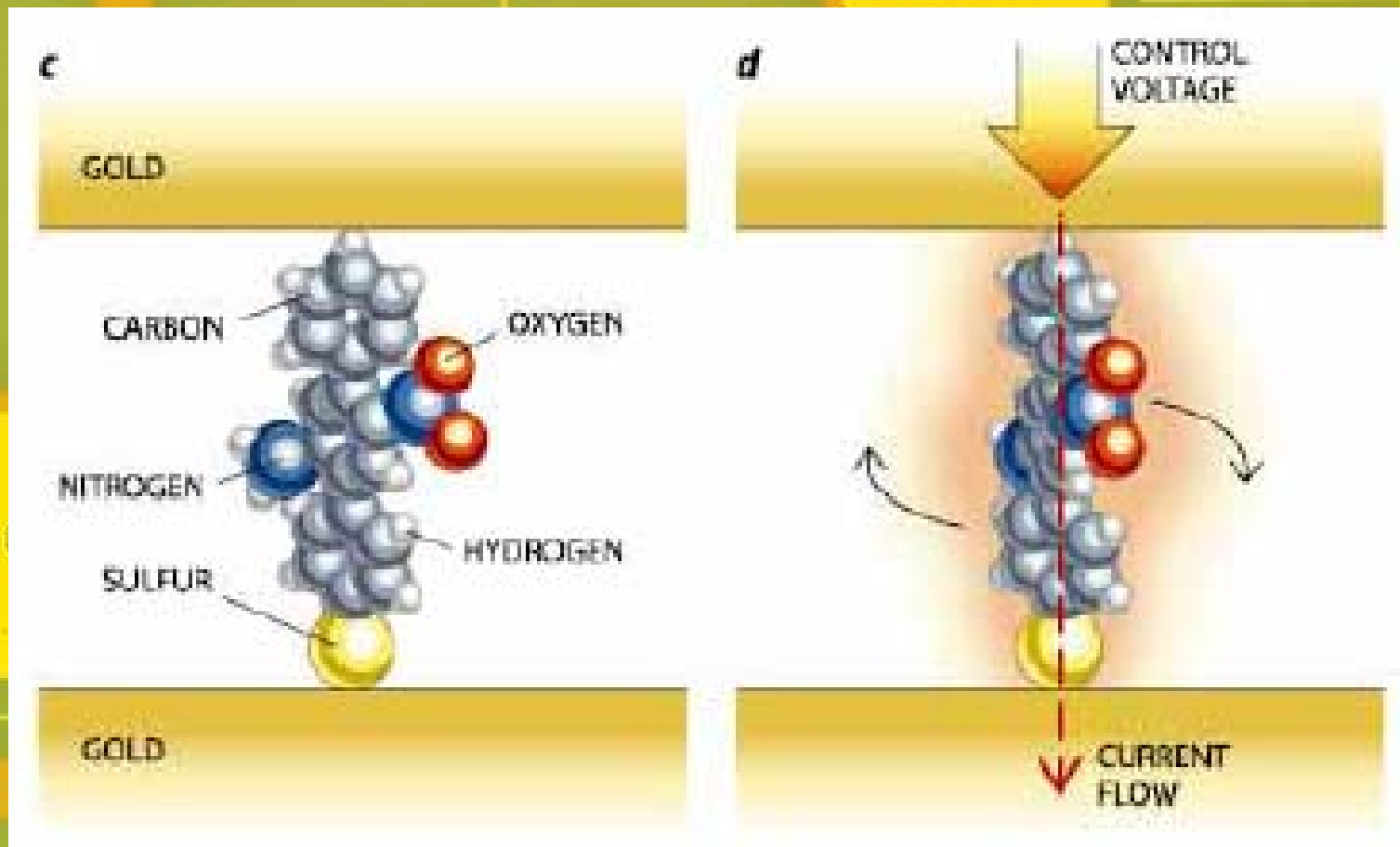


Figure 3

Device characteristics: (a) and (b) Drain current I_D versus V_G and V_D at $V_D = -2$ V and $V_G = -20$ V, respectively; (c) I_D versus V_G at $V_D = -2$ V. The linear regime mobility of $0.122 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$. Reprinted from [15] by permission of Elsevier Science.

Tranzystory na pojedynczych molekułach



Źródła:

- „Field-effect transistors made from solution-processed organic semiconductors” – A.R. Brown w „Synthetic Metals”
- „Organic thin-film transistors: A review of recent advances” – C.D. Dimitrakopoulos z materiałów IBM
- „Organic electronics: Introduction” – J.M. Shaw z materiałów IBM
- „Organic thin film transistors: From theory to real devices” – G. Horowitz
- „Organic Field-Effect Transistors” – G. Horowitz