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Chemical Effects in Organic Electronics

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Effects of the chemical environment on devices utilizing organic semiconductors are discussed. It is convenient and justified to use silicon-based insulated gate field-effect transistors (IGFET) as the yardstick by which the performance of organic field-effect transistors (OFET) are measured. However, the same issues may apply to other types of devices utilizing organic semiconductors (OS). The focus of this article is on chemical modulation of the critical parts of these devices, specifically on the bulk electronic properties, contacts between the metal and OS, and interface between the OS and the insulating support. Controlled interactions between the chemical environment and the solid-state devices have been well documented and utilized in chemical sensors. On the other hand, uncontrolled chemical interactions with a solid-state device may lead to experimental artifacts in electronics that is intended for signal and information processing.

Introduction

It is a generally recognized but not widely appreciated fact that the ambient environment can and does affect organic electronics. This subject has been recently reviewed.[1−3] By “ambient” we mean chemical species in the gaseous atmosphere that surround the device, in which the organic semiconductor (OS) plays a major functional role. The chemical species include both the majority components present in clean air, namely, oxygen, nitrogen, and water vapor, as well as minority components, such as hydrogen, hydrogen sulfide, ammonia, amines, etc. These chemical effects can be reversible or irreversible. In contrast, conventional silicon-based electronics is virtually immune to the environmental interferences because silicon dioxide and silicon (oxy)nitride are almost ideal passivation for most solid-state devices operated under normal conditions. If needed, further protection is provided by additional encapsulation.

The effect of gaseous species on OS is beneficial in solid-state chemical sensors for gases that utilize those materials. In such case, the changes of electronic and optical properties of the OS or the controlled effects on the device structure are the basis of robust and well-functioning transduction principles. In other words, in chemical sensors the OS becomes a vehicle by which the chemical interaction is transformed into defined electrical or optical signal. There is extensive literature covering this subject.[2,4−10] On the other hand, such interactions could be viewed as detrimental in electronics intended for signal and information processing or for optoelectronics.

In this article we take a closer look at the origin and effects that chemical environment can have on organic electronics. We shall consider chemically induced changes in the bulk electronic properties of the OS, namely, the changes of work function (WF) and conductivity, chemically induced changes of the barriers at the OS/metal junctions, and the effect of sorbed species on the interface between the OS and the dielectric substrate that is used as its support.

Practically, any device or a test structure involving the OS can be represented by the equivalent impedance network shown in Figure 1. Chemical effects play separate but specific roles at the individual elements of that circuit, yet measurement of the transfer function at points A and B yields only the overall relationship between applied voltage and the resulting current. It is therefore important to consider the individual impedances separately, because an incorrect assignment of their origin may lead to an incorrect interpretation of the properties of the OS and/or of the function of the

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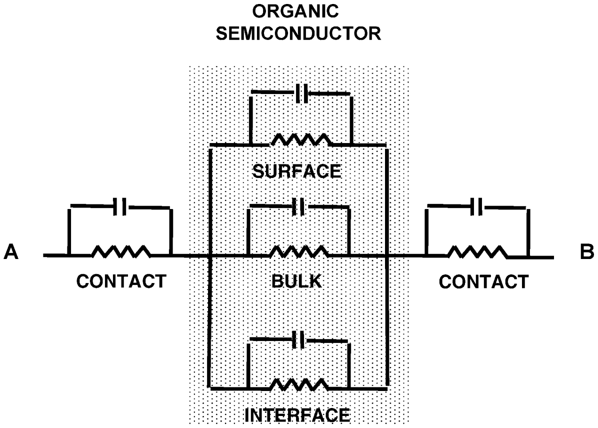

Figure 1. Equivalent circuit diagram of general organic electronic device. The surface, bulk, and interface impedances belong to the organic semiconductor (OS). Contacts represent interface between the metal and the OS.

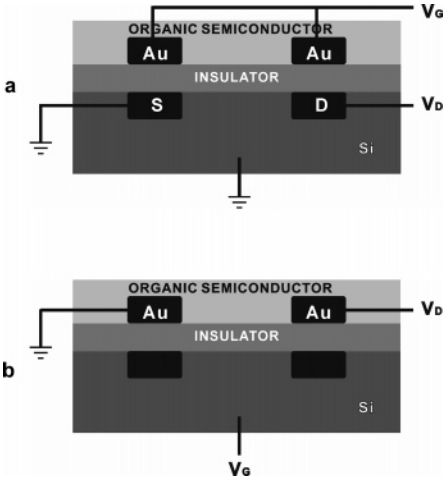

Figure 2. Schematic of the test platform that can be operated as (a) insulated gate field-effect transistor (IGFET) and (b) organic field-effect transistor (OFET).

device. The measurements are done usually in the DC mode; however, including capacitors and presenting the individual circuit elements as impedances, as in Figure 1, has its advantages if the device is investigated by some AC impedance technique. In this paper we examine separately chemical effects on bulk, contacts, and interface.

To elucidate the chemical effects and compare the performance and function of the OS in an "organic field-effect transistor" (OFET) with that of a silicon-based "insulated gate field-effect transistor" (IGFET), the test platform shown schematically in Figure 2 has been designed and fabricated. It has all the features of conventional silicon IGFET except that it has two gate contacts over which the layer of OS gate is deposited. A two-layer gate dielectric is formed by 80 nm of thermally grown SiO_2 and 80 nm of chemically vapor deposited, high-temperature silicon nitride. The detailed description of this platform and its fabrication, characteristics, and use are described in a separate paper.[11] The gate dielectric has sufficient thickness and quality to ensure that there is no parasitic gate leakage current even when unusually high gate voltages (i.e., >20 V) are applied across it. It has been tested in our laboratory with two OS: polyaniline (PANI) and poly(phenylenesulfidephenyleneamine) (PPSA).[12,13] The contacts between Au and either of these two OS are ohmic, as confirmed by examination of the shape of the $I-V$ curves.

When it is operated as a regular IGFET (Figure 2a), a common gate-to-source voltage, V_G, is applied to both contacts and drain-to-source current, I_D, flows in silicon, between n-doped drain and source electrodes. It follows the normal equations valid for IGFET.[14] For $V_D < V_G - V_T$, in the so-called subthreshold (or linear) region, the current is linearly dependent on the applied drain-to-source voltage V_D

$$I_D = \frac{\mu C_0 W}{L}(V_G - V_T - V_D/2)V_D \tag{1a}$$

In the saturation region, $V_D > V_G - V_T$, I_D is independent of V_D but is *quadratically* dependent on $V_G - V_T$

$$I_D = \frac{\mu C_0 W}{2L}(V_G - V_T)^2 \tag{1b}$$

The other parameters in eq 1 are mobility of minority carriers, μ, gate capacitance, C_0, and the geometrical factors of the device, i.e., the width (W) and the length (L) of the channel. The threshold voltage, V_T, is sometimes called the "turn-on voltage" that separates the operation of IGFET in the "ON" and "OFF" state. It is important in defining the "ON/OFF" ratio, which is often used as the figure of merit in the description of OFET. Threshold voltage is also important in ChemFETs because the chemical modulation of the WF of the OS causes the shift of V_T.[9,15,16] Equations 1 describe the well-known transistor characteristics of classical Si-based IGFET. It is therefore not surprising that any deviation from the shape of these ideal characteristics is the first indication of a potential problem in devices that depend on analogous *semiconductor field-effect* in OS.

This platform can be operated also as OFET when it is connected as shown in Figure 2b. In this case the two Au contacts are designated as "drain" and "source", respectively, and V_G is applied to the p-Si substrate. The drain-to-source current then flows *through the organic semiconductor*, and the field modulation takes place in the OS, somewhere in the gate region above the gate dielectric. Again, if the postulated function of the OS is similar or equivalent to the Si, then the output characteristics of OFET should have a similar shape to those obtained with Si-based IGFET of the same geometry. In other words, this platform is a simple diagnostic tool.

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Chemical Effects on Bulk Properties of Organic Semiconductors

The electronic property of greatest interest is the conductivity of the OS and how it can be modulated by the externally applied electrical field. The latter is the key issue for construction and operation of OFET. Conductivity is a function of both the concentrations, n, and the mobilities, μ, of the charge carriers

$$\sigma = n_{\mathrm{n}}\mu_{\mathrm{n}} + n_{\mathrm{p}}\mu_{\mathrm{p}} \tag{2}$$

The subscripts n and p denote electrons and holes, respectively. The external environment affects both properties. The carrier concentrations can be changed by the interactions of the OS with electron donor/acceptor gases, i.e., by formation of a charge-transfer complex. Whether the OS acts as an electron donor or electron acceptor and what fraction δ of charge is transferred depends on the position of the Fermi level of the OS relative to the Mulliken electronegativity of the guest gaseous species.[17–20] In that respect the gas is treated as a secondary dopant.[21–24] Thus, if the electron affinity of the guest gas is lower than that of the host matrix, an electron is transferred from the gas to the OS and vice versa. The shift of the Fermi level, ΔE_{F}, resulting from this charge transfer is related approximately to the partial pressure, P_{G}, of the host gas present in the mixture of background gases ΣP_{j}[25]

$$\Delta E_{\mathrm{F}} = \mathrm{const.} + \frac{kT}{2\delta}\ln(PC + \sum P_{\mathrm{g}}) \tag{3}$$

Since the majority of the OS used in organic electronics are p-type materials, their interaction with electron donors lowers the density of holes and leads to lowering of their conductivity, according to eq 2. That effect has been utilized in the design of chemical sensors called *chemiresistors* in which conducting polymers form the selective layer of the sensor.[8,26,27] The effect of ammonia on the conductivity of undoped PANI is shown in Figure 3. It has been measured in the OFET configuration. The resistivity of undoped PANI estimated from these measurements is approximately $\rho = 1.8 \times 10^5$ Ω cm, increasing 100% upon exposure to ammonia. The relative change of conductivity upon exposure of the OS to NH_3 illustrates the chemical effect on bulk conductivity of this material. It should also be noted that there is no semiconductor field-effect according to eq 1, only an ohmic dependence of current on applied V_{D}. Similar effects have been described for poly(3-hexylthiophene).[28]

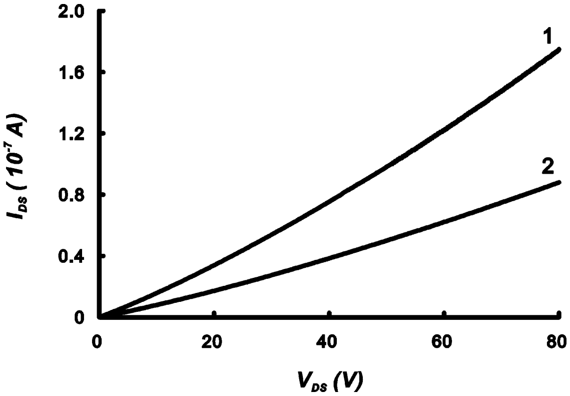

Figure 3. Effect of ammonia on OFET characteristics of undoped PANI: (1) pure nitrogen; (2) ammonia (1000 ppm) in nitrogen. The scan rate was 316 mV s^{-1} and the gate voltage $V_{\mathrm{G}} = 0$ V. The measurement was done with a semiconductor parameter analyzer, HP 4155A.

The mobility, μ, can be also affected by interaction of the gas or vapor with the OS, which causes its swelling.[10,29,30] In this case the carrier hopping distance is affected, i.e., the mechanism of response of certain chemiresistors, but, to our knowledge, it has not been considered as being important in other forms of organic electronics.[10,26,27]

Another key property of electronic materials that impacts their use in solid-state devices of any kind is their electron affinity, i.e., their work function (WF). It is defined as the energy required to remove an electron from the Fermi level of the material and deposit it in the vacuum reference level, which lies outside the electrostatic field of that phase. The work function of a single material is not experimentally accessible. However, the difference of the WF of two materials can be measured by a variety of methods of which the vibrating capacitor (Kelvin probe) or a field-effect transistor (also a capacitor) are the best known.[31] The difference of the WF enters this discussion in two places. First, the difference of the WF of silicon and OS affects the threshold voltage of devices that rely on the *semiconductor field-effect*. Second, it affects the quality and type of contact between OS and metal in the OFET.

The chemical modulation of the WF of OS has been successfully utilized in chemically sensitive field-effect transistors (ChemFET) for detection of gases according to eq 3.[4,17,32] In this case, the WF of silicon is constant and the response is due solely to chemical modulation of the WF of the organic semiconductor.

Chemically Induced Effects at the Organic Semiconductor/Dielectric Interface

It was recognized 40 years ago that the surface conductivity of the dielectric substrate can have a detrimental effect on the performance of solid-state electronic devices.[33] A concentrated effort has been made

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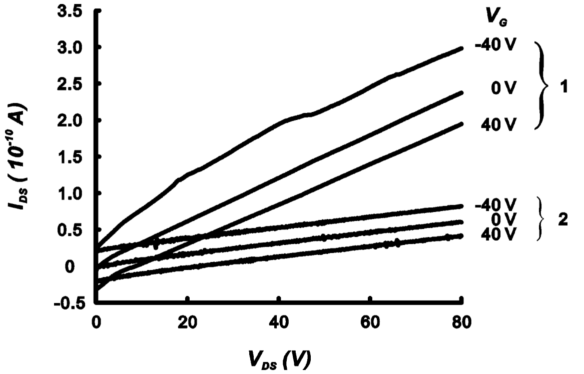

Figure 4. Effect of parasitic conductance due to the hydration of the interface between OS and silicon (oxy)nitride in the OFET mode. The device used undoped PPSA for the OS (see Figure 2). (1) Devices hydrated in water for 10−15 min. (2) "Dry" OFET/IGFET chip that was dehydrated in a vacuum oven at 88 °C for 12 h. The $I_{DS}-V_{DS}$ curves were recorded for sets of three gate voltages, as shown, at a scan rate of 1 V s^{-1}. These currents are at the limit of the measuring capability of the semiconductor parameter analyzer, HP 4155A (10 pA). The offsets observed for different gate voltages are due to input bias voltage error. Therefore, only the relative changes of conductivity are meaningful.

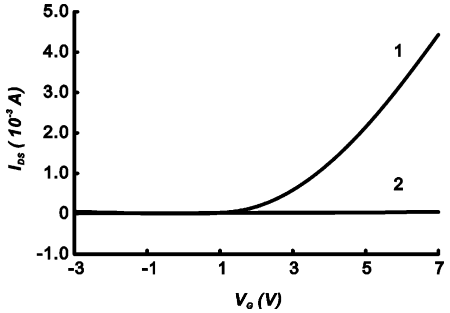

Figure 5. Effect of hydration on IGFET mode of operation. There is *no OS* deposited on the silicon (oxy)nitride, and the I_D modulation by applied V_G is due only to the surface conductivity of the silicon (oxy)nitride. $I_{DS}-V_{GS}$ curves were recorded for $V_{DS} = +5$ V at 100 mV s^{-1}. (1) Device hydrated in water for 10−15 min. (2) "Dry" OFET/IGFET chip that was dehydrated in a vacuum oven at 88 °C for 12 h. Curve 1 is identical to the one obtained with any OS gate, e.g., one shown in Figure 9a.

to minimize the influence of possible parasitic pathways. The insulating substrates are typically oxides (e.g., glass, quartz, sapphire, etc.). It is known that the surface conductivity of the oxides changes with the amount of sorbed water, making water the most common interferant for devices that are operated at room temperature and in ambient atmosphere.[34−40] Water is not unique in this respect. Other amphiprotic molecules, such as alcohols, organic acids, amines, etc., can chemisorb on such surfaces and increase their interfacial conductivity. The chemisorbed water is difficult to remove, and heating in a vacuum above 100 °C is usually required to minimize the effect of surface hydration.[41] At the relatively high voltages that are used for operation of some devices, the electrolytic decomposition potential of hydrated oxides at the interface of the metal contact and the hydrated surface of the insulator is easily exceeded, leading to electrolytic decomposition at the interface. When the parasitic current becomes comparable to the current flowing through the OS, interpretation of the results becomes problematic.

Since the OFET materials have very low conductivity, the danger of creating a competing parasitic conductive pathway that parallels the conductance through the OS is very real. In Figure 4 the current flowing through an undoped (i.e., highly resistive) OS is compared for a (1) "hydrated" and (2) "dehydrated" device, operated in the OFET mode. When the adsorbed water is removed from the interface, the measured resistance decreases by 75%. Similar measurements were made also in the IGFET mode, with the chip that had *no OS in the gate region*. If the interface is conducting (i.e., wet), it is possible to apply common V_G to both Au electrodes and thus obtain regular IGFET characteristics (Figure 5, curve 1). However, when the interface is dry (i.e., nonconducting), the device behaves like a normal "floating gate" IGFET (Figure 5, curve 2) and no drain current modulation is possible. There is no effect of hydration when an OS is deposited over a wet or dry interface. In this case molecules adsorbed at the interface affect the threshold voltage of the IGFET only by their dipolar contribution to the electric field.

Interfacial currents following other parasitic pathways at the wire-bonded devices may be also observed. They depend on the specific geometry of the device, how it is connected to external instrumentation, and the materials used. Obviously, when a high voltage, on the order of tens of volts with respect to ground, is applied to any contact, different parasitic leakage current pathways may be created. This is particularly true when a high voltage is applied to the OS, which itself has a very low intrinsic conductivity.

Another type of leakage current is due to the dielectric breakdown of the gate insulator under high applied electrical field. In the case of a silicon dioxide/silicon nitride gate insulator, such leakage, also known as "punch-through", occurs when the electric field exceeds 10^5 V cm^{-1}. For this reason, the applied gate voltages in silicon transistors are rarely higher than 20 V. It is not possible to predict when such failure may take place because it depends on the types of materials used, the density and location of the defects, and the geometry of the device. In our OFET/IGFET platform the gate failures have sometimes occurred at $V_G > 60$ V.[11] The presence of gate leakage currents can and should be always measured and reported. As the general rule, the sum of the leakage currents should not exceed 0.1% value of the measured I_D.

Chemical Effects on Electrical Contacts

The physics of charge carrier injection through an interface separating a metal and an organic material strongly depends on the equilibrium dark conductivity

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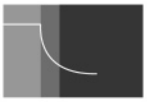
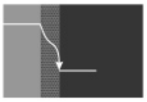
Table 1. Four Types of Contacts Encountered in Organic Electronics

TYPE	EXAMPLE	POTENTIAL PROFILE	CURRENT EXPRESSION
Ohmic	Au/PANI		$J \sim V \exp\left(\frac{-c}{T}\right)$
Fowler-Nordheim	Al/Al_2O_3/PANI "????"		$J \sim V^2 \exp\left(\frac{-b}{V}\right)$
Schottky	Au/Cr_2O_3/PANI + "????"		$J \sim T^2 \exp\left(\frac{a\sqrt{V}}{T} - \frac{q\phi_b}{kT}\right)$
Frenkel-Poole	ITO/PANI + Cr_2O_3,TiO_2; "????"		$J \sim V \exp\left(\frac{2a\sqrt{V}}{T} - \frac{q\phi_b}{kT}\right)$

"????" = IMPURITY

of the OS. In undoped OS the density of free charge carriers is very low, exhibiting insulating behavior. Therefore, the Schottky depletion region cannot be formed at a metal/OS interface. The conductance in an ideal insulating film is assumed to be zero. However, low doped semiconductors, just like real insulators, show carrier conduction when the electric field or the temperature is sufficiently high. Table 1 summarizes the basic conduction processes in contacts.[14] For a given contact, each process may dominate at certain temperature and voltage ranges and these processes are also interrelated.

Ohmic Contacts. For efficient operation of the device, the contacts must be ohmic. If this is not the case, there is a limitation depending on the nature of potential barriers existing at the contacts that can be controlled by energy barriers across the ohmic metal/OS interface.[42] Although contact potential exists at the ohmic metal/OS interface, it is not subject to chemical modulation and the applied voltage falls across the bulk of the OS. The charge-injecting electrode has no significant resistance and is able to supply any current required by the bulk. When such contact is made to an undoped organic semiconductor, which has no free carrier density, the current is limited by bulk space−charge effects which result from carriers injected into the undoped polymer, where no compensating charge is present.[43] Modeling shows that for ohmic contact between metal and low-mobility OS, the barrier to carrier injection has to be lower than about 0.3−0.4 eV [44,45]

Gold and indium−tin oxide (ITO) are commonly used to form an ohmic contact with most of the p-type OS. The electrical properties of ITO vary considerably with chemical composition and processing history. Work functions determined by different measurements vary from 4.0 to 5.2 eV for a range of commercial ITO samples.[43] This is in agreement with measurements which show that ITO with WF of 4.8 eV forms an ohmic contact with an OS with an ionization potential I_P = 5.1 eV but a blocking barrier contact with a OS with I_p = 5.4 eV.[46,47]

The work function of gold has been assumed to be about 5.0−5.2 eV. Several studies show that the work function of π-conjugated polymer films is about 5 eV. In this case, the barrier between the p-type polymer and gold is relatively small, representing a quasi-ohmic contact, with a symmetrical and linear current−voltage dependence.[48−52] Nevertheless, the experimental contacts are sometimes rectifying, indicating a higher WF of the OS than that of gold.[52]

Barrier Contacts. In general, dark carrier injection over a barrier into insulators, i.e., undoped organic semiconductors, follows the Richardson−Schottky and Fowler−Nordheim models. The former deals with thermally activated over-barrier injection; the latter emphasizes the tunneling charge injection through a triangular barrier.[53] Analysis of high work function metal/OS interfaces shows that the $I-V$ characteristics depend not only on the applied voltage but also on the electric field at the contact, the temperature, and impurities. This clearly points to a tunneling model for carrier injection in which the carrier is field emitted through a barrier at the electrode/OS interface.[54] These barriers may be caused by interaction of the OS with the metal, interaction of both with ambient air, e.g., by metal oxide formation, or overoxidation of the OS. The last three are chemical by nature. They change the local band structure of the OS/metal interface. They may also offset the energy bands at the interface and the electrode through which holes and electrons are tunneling when the applied electric field tilts the OS bands.

It is obvious that the current−voltage characteristics are sensitive to the barrier height. Since the current density depends on the applied voltage, we can see that increasing the barrier height, even slightly, leads to an exponential decrease in current (Table 1). This type of charge transport is considered to occur under high electric field in both undoped OS as well as metal oxide layers, e.g., Al_2O_3 and Cr_2O_3. (Table 1)

Chemical modulation of the barrier can occur in different ways depending on the chemical properties of the contact materials. This modulation involves contamination of noble metal surface by metal oxides or aging of low WF metal electrodes, such as chromium, silver, or aluminum. Since metal oxides have a lower WF than the parent metal, those changes can be in the range of several hundreds of millielectronvolts. The

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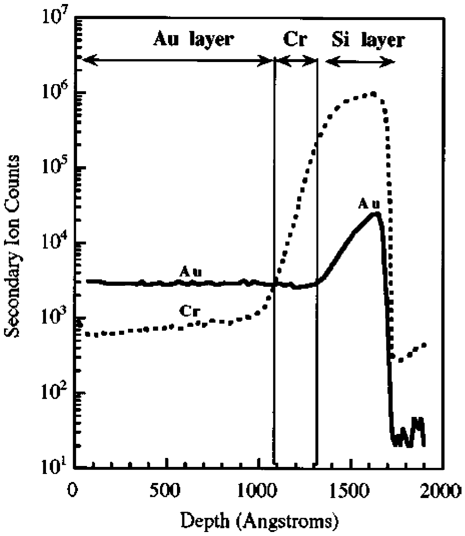

Figure 6. Depth profiles of atomic composition of Au/Cr/Si contact obtained by time-of-flight secondary-ion mass spectrometry. Note that Cr is present both within and at the surface of the Au. (Reprinted with permission from ref 55. Copyright 1998, American Institute of Physics.)

resulting charge carrier injection rate can vary by several orders of magnitude.

Molecular modeling which includes specific chemical reactions between the metal and the OS has been done.[56−58] On the basis of such calculations, it has been postulated that the metal plays an important role in determining the extent of charge transfer at the metal/OS interface: Ca and Na appear to transfer charge at the interface without significantly altering its chemistry.[56,60] However, these low-WF metals are notoriously unstable in air.

Gold forms ohmic contact with most p-type OS layers. In OFETs utilizing Au bottom electrodes, over which the OS is deposited, the current density shows a linear dependence on the applied electrical field, indicating an ohmic behavior, as long as no "glue metal" is used to increase the adhesion of Au on the substrate. A non-ohmic behavior can be observed, and the hole injection efficiency is significantly degraded when Au is evaporated onto Si using a thin Cr adhesive layer. The severe depression of the hole injection efficiency from the Au/Cr substrates appears to be associated with the known contamination of the Au surface by Cr at the OS/metal surface.[55] The chromium atoms migrate along the grain boundaries of polycrystalline Au to the surface of Au and form Cr_2O_3 at the Au surface.[61] This contamination affects the surface properties of the noble metal by lowering its WF. A depth profile (Figure 6) of an Au/Cr/Si layer by TOF−SIMS shows the presence of chromium atoms within and at the surface of the Au substrate.[55]

The contamination effect can be generally observed for glue metals as well as for barrier metals, used for deposition of thin films of noble metals on oxide surfaces. The surface contamination of the noble metal layer is an ongoing process affected by several parameters, namely, temperature, grain size of the noble metal, and degree of oxidation of the glue/barrier metal. It affects the long-term behavior of the contacts and is known as "contact aging". Interestingly, response of OFET with (undoped) PANI as the OS to chloroform has been interpreted as a "semiconductor field-effect" response.[62] In that report Au/Cr/SiO_2 contact was used. The reported I_D-V_D curves have characteristics of high serial contact resistance, indicating that it is the modulation of the contact resistance that is responsible for the observed effect.

The method of choice for metal contact deposition in organic devices, such as light-emitting diodes or thin-film transistors, is evaporation.[63] However, the nature of the electrical contact can be affected by chemical damage to the OS during that process. The contact properties of a metal evaporated *on top* of the OS can differ markedly from the contact properties of the same metal when the OS is coated onto a bottom metal electrode. It has been observed that the presence of a blocking interface in the top contacts is not consistent with the estimation of the injection barrier height from the relative WF of the interface components.[55,64] This observation is not unique to an Au/OS interface, having been confirmed also for evaporated Ag and mechanically made liquid Hg contacts.[64] The nature of evaporated Au top electrodes and the possible damage to the OS can vary with the number of deposition steps and evolve from blocking to ohmic with time and temperature.[55,64] This is attributed to the physical or chemical changes of the organic material at the interface during the metal deposition.

Another source of the barrier formation at the electrical contact in organic devices is due to the changes of the electronic properties of the OS when it is stored in ambient atmosphere. Water vapor irreversibly reduces the density of trapping and doping states in the band gap.[65] The combined effect of oxygen and water at the contact can cause irreversible overoxidation and formation of organic carbonyl groups at the conjugated polymer. When that happens the π-electron system is interrupted, resulting in reduced carrier mobility.[66]

Poly(3-alkyl thiophenes) are solution-processable semiconductors with the highest charge-carrier mobility reported. Practical use of this class of semiconducting polymers, however, is restricted by their limited stability in air and light, due to oxidative doping.[67] A reversible

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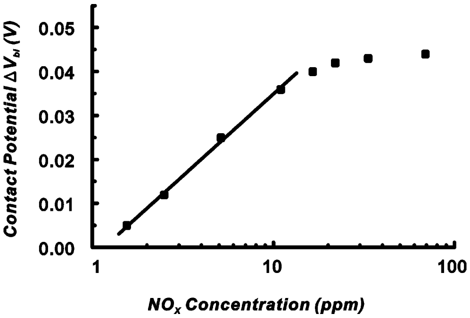

Figure 7. Gas-induced change of the contact barrier characteristics of a PPy/Au metal junction as a function of NO_x vapor concentration in ambient air.[71]

effect of oxygen on structures based on poly(3-alkylthiophenes) has been observed.[65,68,69] Oxygen induces acceptor states and fills the traps in the band gap. Analysis of poly(3-hexylthiophene) field-effect transistors shows that the extent of the reversible modulation of electronic properties is proportional to the oxygen partial pressure.[69] In the absence of oxygen, a typical FET-like response is observed, i.e., clear saturation currents, which are proportional to the gate bias. In the presence of oxygen, the current increases by an order of magnitude, the charge carrier mobility is lowered by the formation of the charge-transfer complex, and the curves take on considerable "ohmic" behavior. These *I*−*V* curves are fully reversible upon removal or addition of oxygen.

Studies of the effects of ambient atmosphere on contacts have focused mainly on oxygen. However, the effect of other gases has been documented, mainly from the sensing point of view.[3,70] Figure 7 shows the dependence of the change of the contact potential of a polypyrrole/Au metal junction on the NO_x concentration. It can be clearly seen that the change of the contact potential is exponentially dependent on the NO_x concentration, indicating the dependence of the WF on the charge-carrier concentration according to eq 3.[71]

Semiconductor/metal interfaces form the basis of many rectifiers, point contact diodes, metal−semiconductor field-effect transistors, surface barrier chemical sensors, and other surface junction devices. In practice, even if all WF (Fermi levels) were matched exactly to the highest occupied molecular orbital (HOMO) or lowest unoccupied molecular orbital (LUMO) levels, there exists a finite probability of having potential barriers at all junctions possibly due to surface states, impurities adsorbed during junction formation, and possible chemical reactions between the materials contacted. In principle, these junctions behave as parasitic nonlinear resistances in series with the linear source and drain access resistances. Their effect on the shape of the I_D−V_D and I_D−V_G characteristics is shown in Figure 8b and Figure 9b, respectively. The distortions are clearly evident from comparison with normal IGFET characteristics shown in Figure 8a and 9a.[72] It is obvious that transistors with serial contact resistance do not follow the ideal curves, given by eq 1.

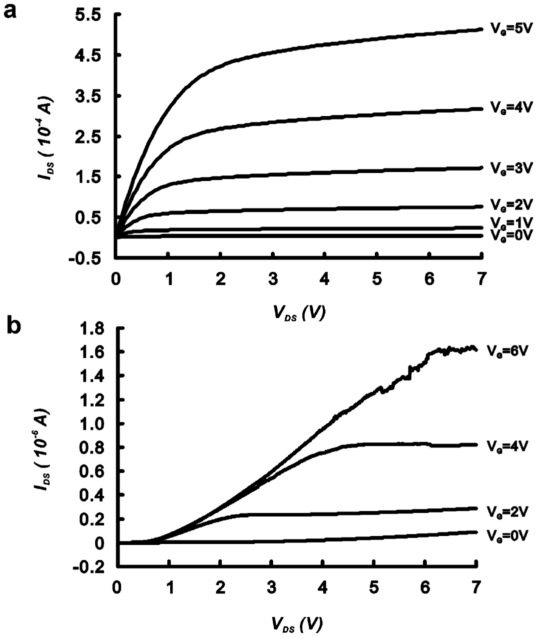

Figure 8. Comparison of I_D−V_D characteristics of silicon IGFET (a) without and (b) with contact resistance. The contact resistance was formed by a layer of SiO_2 at the Si/Ti,W/Au contact.

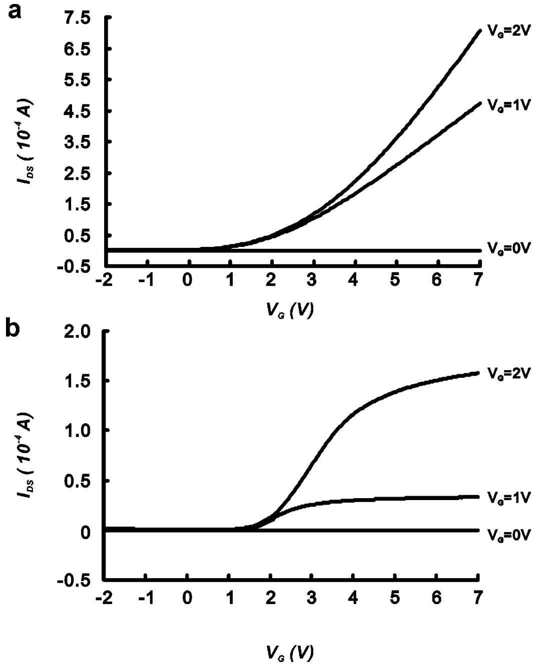

Figure 9. Comparison of I_D−V_G characteristics for the same IGFET (a) without and (b) with contact resistance.

The presence of contact resistances and their effect on the transistor characteristics have to be considered when developing OFET in order to interpret nonlinearities in the current−voltage characteristics correctly. The IGFET/OFET platform discussed in this paper allows one to distinguish between the field modulation

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of the semiconductor resistance in the gate channel and that of the metal/OS source and drain contacts. It can help to optimize the OFET with respect to the quality of contacts and to study and improve independently the electronic properties of the OS layer.

Conclusions

The main culprits of chemical effects in organic electronics are oxygen and water, although other minority components in the ambient atmosphere can affect the organic electronics just as well. That phenomenon is utilized in solid-state gas sensors that use *the same or similar OS*. Some of those effects are reversible, i.e., secondary doping of bulk of the OS with oxygen, but some are irreversible, i.e., formation of barrier oxides on metal contacts. Since oxygen and water are the major components of ambient atmosphere, they always have to be taken into account when designing, fabricating, and testing organic electronic devices.

Organic electronics is a new technological area that attracts a great deal of attention. It promises to offer a wide range of interesting applications that would be complementary to but otherwise not attainable with conventional silicon electronics. The importance of understanding and controlling the chemical environmental factors is critical for both solid-state chemical sensors and organic electronics intended for signal and information processing. Failure to do so may result in experimental artifacts, and incorrect allocation of developmental resources. It is particularly important in organic electronics in which the OS are subjected to high applied voltages that are close to the breakdown limits of many materials and structures. Such breakdowns increase the danger of parasitic current pathways that may lead to misinterpretation of some measurements. To diagnose this risk, a new test platform has been developed that allows direct comparison of performance of the OS in the OFET as well as in the IGFET configuration.[11] Its function in the context of the chemical effects is described also in this article. It is clear that the importance of performing a baseline test, particularly measurements of various parasitic leakage currents, should not be underestimated.

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