



Review

Carbon nanotubes based transistors as gas sensors: State of the art and critical review

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ABSTRACT

In this paper we present recent studies concerning gas sensors based on carbon nanotube field effect transistors (CNTFETs). Although these devices have allowed one to realize sensors with an impressive sensitivity compared to existing technologies, the physical interpretation of the interaction between the gas molecules and the CNTFETs has not been clarified yet. In this contribution, we try to find some consistency between the physical interpretations advanced by the different scientific teams working on the subject and to answer some unsolved questions. Moreover, considering that the selectivity is the main issue, we analyze the different routes that have been proposed to overcome this problem: functionalization using polymers, diversification of the source/drain metal electrodes, metal decoration of SWCNT mats, exploitation of the desorption time of the different gases. For each technique we try to evaluate the advantages and the drawbacks.

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1. Introduction

Carbon nanotubes (CNTs) are one-dimensional molecular structures obtained by rolling up one graphene sheet into a seamless cylinder (single-wall-carbon-nanotube, *i.e.*, SWCNT) or more (multi-wall-carbon-nanotube, *i.e.*, MWCNT). Since their discovery in 1991 [1], many scientific teams have focused their interest on this novel material which shows extraordinary physical properties. Actually, CNTs have demonstrated very high carrier mobility in field effect transistors [2], a very high electromigration threshold (10^8 – 10^9 A/cm² [3]), a very high thermal conductivity (for a single tube, it can reach 3000 W/AK [4–6]) and exceptional mechanical

properties (the measured specific tensile strength of a single shell of a MWCNT can be as high as 100 times that of steel [7]). Therefore, CNTs are studied for many applications: for field emission devices [8–12], for composites, in order to improve electrical or thermal management as well as mechanical resistance [13,14], for electronic devices, to replace silicon based transistors [15,16] and finally, for chemical and biological sensors [17–19]. Concerning this last application, different kind of gas/chemical sensors, based on different working principles, have been fabricated thanks to CNTs: miniaturized ionizing gas sensors (also called “micro-gun” sensors) [20], CNT thin films with variable resistance as a function of the adsorbed gas properties [21–24] and finally carbon nanotube field effect transistor (CNTFET) based sensors. The main advantages for CNTFET based sensors, compared to existing technologies, are numerous, since devices can be made ultra compact, effective at room temperature, with a low power consumption, a very fast response time, a low

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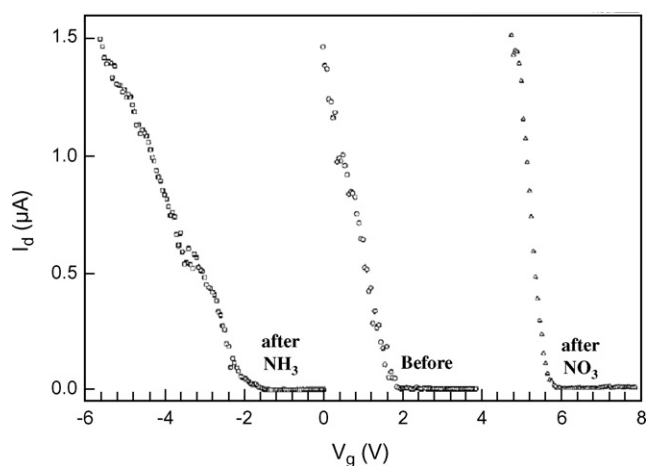


Fig. 1. Transfer characteristic change after exposure to NO_2 and NH_3 of the first CNTFET gas sensor fabricated at Stanford in 2000 by Kong et al. [26]. Gas-sensing experiments were carried out by placing CNTFETs into a sealed glass flask and exposing to NO_2 [2–200 parts per million (ppm)] or NH_3 (0.1–1%) in Ar or air (flow rate of 700 ml/min). The channel length was around $5 \mu\text{m}$.

recovery time (few seconds) and they show a good versatility (*i.e.*, they can be used for several gases). Finally relatively low fabrication costs can be reached, considering that CMOS compatible technology can be employed. It has to be pointed out that for this kind of sensors, the research has essentially focused on SWCNTs (which can be semiconducting or metallic, depending on their chirality [25]) because MWCNTs are only metallic and therefore unsuitable to fabricate transistors.

This paper deals with the state of the art in the domain of CNT-FET based gas/chemical sensors and intends to review the different physical arguments developed to explain the gas/device interaction, trying to find some consistency between them, in order to answer the different unsolved questions. A section is devoted to the different routes developed to improve selectivity. This is a very important issue, considering that a high selectivity is the key factor to definitively strike huge markets such as security (*e.g.*, detection of warfare gases such as nerve agents or detection of traces of highly volatile and explosive gases), healthcare (*e.g.*, NO sensors for asthma monitoring or CO_2 for emergency airway management), safety (*e.g.*, sensors for the detection CO or benzene, toluene, ethylbenzene, and xylenes, commonly called BTEX group) and environmental monitoring (*e.g.*, NO_2 , benzene).

2. Gas–CNTFET interaction: gas-induced doping or Schottky barrier modulation?

The first paper showing the great potentiality of CNTFETs for gas sensing applications was published in 2000 [26]. In this paper Kong et al. at Stanford University observed that a single SWCNT used as a transistor channel between two gold electrodes, fabricated on a SiO_2/Si substrate acting as a bottom gate, interacted with gas molecules, changing the CNTFET transfer characteristics (source-to-drain current as a function of the gate voltage). The gases used for tests were NO_2 and NH_3 with concentrations between 2 and 10,000 ppm. These gases were chosen because they exhibit two opposite electronic behaviours as a consequence of their chemical affinity: the first one is an “electron-acceptor” gas (thus inducing p-type doping of the SWCNT) and the second one is an “electron-donor” gas (inducing n-type doping).

The experimental results pointed out an increase and a reduction of the p-type CNTFET conductance for NO_2 and NH_3 , respectively (Fig. 1). Concerning NO_2 , its interaction with the nanotube was interpreted as strictly connected to a bulk doping effect.

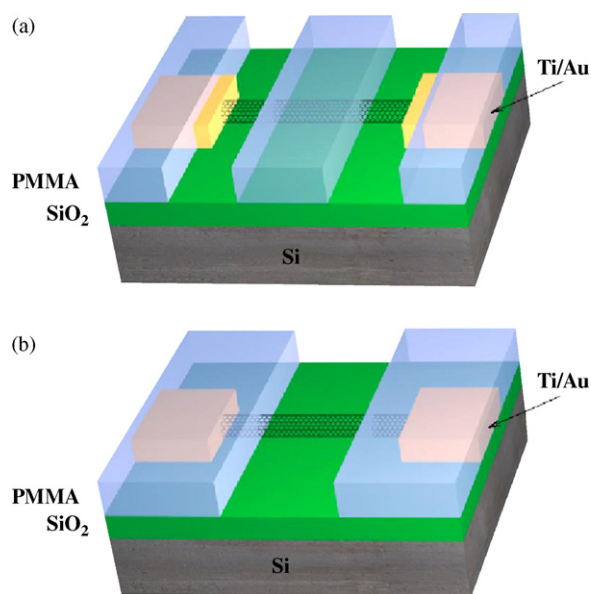


Fig. 2. Configurations of CNTFETs for the tests performed at the University of South California by Liu et al. Schematics showing the CNTFET zones exposed to gas species: (a) center-covered configuration, (b) contact-covered configuration [31].

Actually, NO_2 can be bound to a semiconducting nanotube with a subsequent electron charge transfer from the tube to the adsorbed molecules [27–30]: the hole carrier concentration in the nanotube increases and so does the conductance, with a consequent shift of the activation bias (V_{ON}) to a larger positive voltage. This effect has been assimilated to a sort of “molecular gating” of the carbon nanotube, due to the gas molecules adsorption. On the contrary, NH_3 molecules, as it has been demonstrated, have no binding affinity with semiconducting SWCNTs [27–30]. The Stanford team invoked two possible reasons in order to explain the effect of the NH_3 molecules on the CNTFET channel:

- The binding between NH_3 molecules and the hydroxyl groups on the SiO_2 substrate leading to a reduction of the negative charges on the oxide and equivalent to a positive electrostatic gating of the SWCNT.
- The interaction of NH_3 with oxygen species adsorbed on SWCNT.

Liu et al. at the University of Southern California (USC) [31], performed in 2005 measurements on the same type of devices tested by Kong et al. at Stanford, and constituted by a single SWCNT as CNTFET channel. Experimental tests were performed on the CNTFET exposed to concentrations varying from 0 to 4 ppm of NO_2 and from 0 to 400 ppm of NH_3 , covering alternatively the metal/SWCNT contacts and the center of the channel (Fig. 2) with polymethylmethacrylate (PMMA) resist. In both cases, the results showed an increase of the V_{ON} for NO_2 (shift to higher positive value) and a reduction of the V_{ON} (shift to higher negative value) for NH_3 (Fig. 3). These results were explained as before [26], by calling upon the doping of the SWCNT (for the NH_3 as well, in spite of the weak NH_3 –CNT binding). The conclusion of the USC researchers was that the CNTFETs were sensitive to gas exposure even if metal/CNT junctions were covered.

Qualitatively, the results of Liu et al. and those of Kong et al. are similar. The main difference probably concerns the recovery time between two successive measurements. In fact, the Stanford team succeeded in recovering the initial transistors characteristics by heating the sample during 1 h at 200°C in air or by exposing the sample to pure Ar (at room temperature) for around 12 h. In a different way, for nearly the same gas concentrations, the USC team

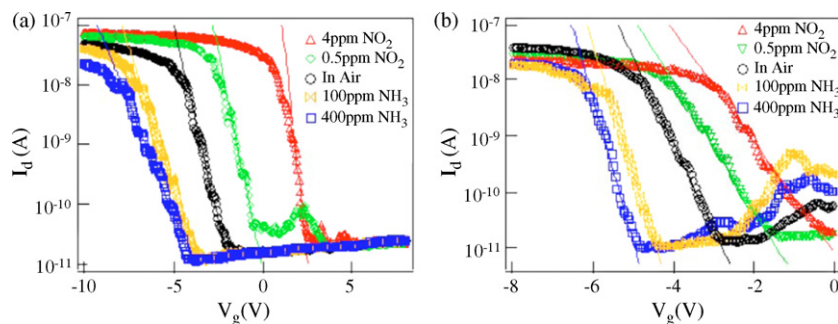


Fig. 3. Results of the tests performed at the University of South California by Liu et al. in 2005, after exposure to different concentrations of NO_2 and NH_3 for the center-covered configuration (left hand side) and contact-covered configuration (right hand side) [31]. The SWCNT was $4\ \mu\text{m}$ long. The measurements show a change of the transfer characteristics for both configurations (see text for comments).

left the samples for 30 min in air to recover the initial signal. This last detail could be a very important issue because it might have given rise to a misinterpretation of the experimental results: a too short recovery time could not allow the complete desorption of gas molecules on the carbon nanotubes or on the oxide after previous measurements. These adsorbed molecules may have altered the final results. Also, in the situation where the contacts were covered, the extent of the passivation region from the contact was not specified in Liu's experiments, which can be an important parameter to take into account since the interface between the nanotube and the PMMA certainly acts as a short circuit for gas diffusion to the contact area. In other words, there should be a difference between the situation where the contacts are covered and the situation where the body of the nanotube is covered (see below).

Up to now, we have analyzed the works of research teams that attribute the key role in the CNTFET sensing essentially to the body of the nanotube and not to the metal/SWCNT junctions. In fact, they assert that the gas molecules dope the nanotube and so change its conductance. However, several scientific teams have adopted a different point of view and have focused their studies on demonstrating that the metal/SWCNT junctions are the key players in the sensing mechanism.

In this context, one of the most interesting studies has recently been published by Geogestown University [32]. In 2006, they fabricated CNTFETs using two Pd electrodes on a SiO_2/Si substrate (bottom gate configuration). In order to evaluate the effect of metal/SWCNT contacts, they covered these contacts with a 200 nm-thick layer of PMMA, followed by a $2\ \mu\text{m}$ -thick layer of SU8, an epoxy-based photoresist (Fig. 4a). After having exposed the CNTFET to a concentration of NO_2 increasing up to 200 ppm (NO_2 was mixed to N_2 at atmospheric pressure), they did not observe any change in the transfer characteristic of the CNTFET during the first 30 min, compared to their results in ambient air. After 30 min, the saturated conductance increased very slowly with time. This change of conductance was interpreted and modeled as the direct consequence of the diffusion of the gas molecules through the polymer layers, down to the contact regions. The same result was obtained for a wholly covered device (Fig. 4b), demonstrating that the NO_2 molecules had no doping effect on the channel of the CNTFET. For these measurements, the total recovery time was around one day of CNTFET exposure to ambient air, which is consistent with the experiments of Kong et al. [26].

Another team that has been working for 10 years on CNTFET issues, is the IBM team in Yorktown Heights, led by Avouris. Their work, even if not focused on sensor issues, is an important contribution for the understanding of the effect of oxygen, and more generally of gases, on the behaviour of CNTFETs. They underscored that CNTFETs operate as unconventional Schottky-barrier transistors and that the effect of adsorbed gases, e.g., O_2 , can be explained by their influence on the metal electrode work-functions. The IBM

team demonstrated that if a CNTFET (exhibiting a p-type behaviour in air) was annealed in vacuum at 600 K for several minutes, it converted to an n-type device. They asserted that this phenomenon could not be explained by oxygen doping [33–35]. Indeed, assuming that the carbon nanotube was initially p doped by oxygen, they could not explain why the annealing (supposed to desorb oxygen) allowed one to obtain an n-type SWCNT and not an intrinsic one. Moreover, supposing that the SWCNT was originally doped by oxygen, the change of oxygen concentration, and so of doping, would have given rise to a shift of the V_{ON} of the CNTFET. Actually,

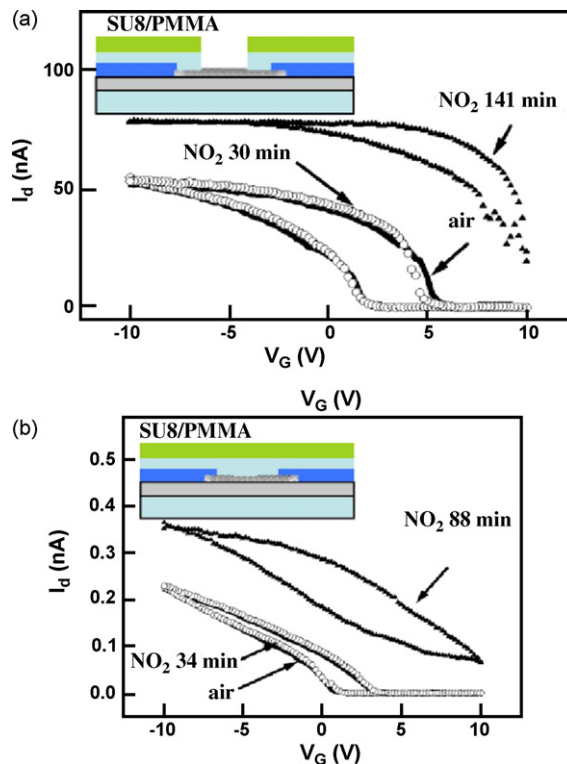


Fig. 4. Results of the tests performed at Geogestown University by Zhang et al. Transfer characteristics change for a CNTFET in contact-covered configuration (a) and fully covered (b) for different exposure times to NO_2 [32]. The channel was around $6\ \mu\text{m}$ long. The principal effect seems to be related to the interaction between the gas specie and the metal/SWCNT junctions. In both cases there is no measurable change of the transfer characteristics during the first 30 min of exposure. After this period of time NO_2 molecules reach the transistor contacts, diffusing through the PMMA and SU-8, and change the CNTFET response. The characteristics for 141 and 88 min of exposure to NO_2 are very similar in (a) and (b) respectively, i.e., whether the body of the nanotube is covered or not. This indicates that there is no doping effect of the NO_2 molecules on the SWCNT. These results are in contradiction with those of Liu et al. [31].

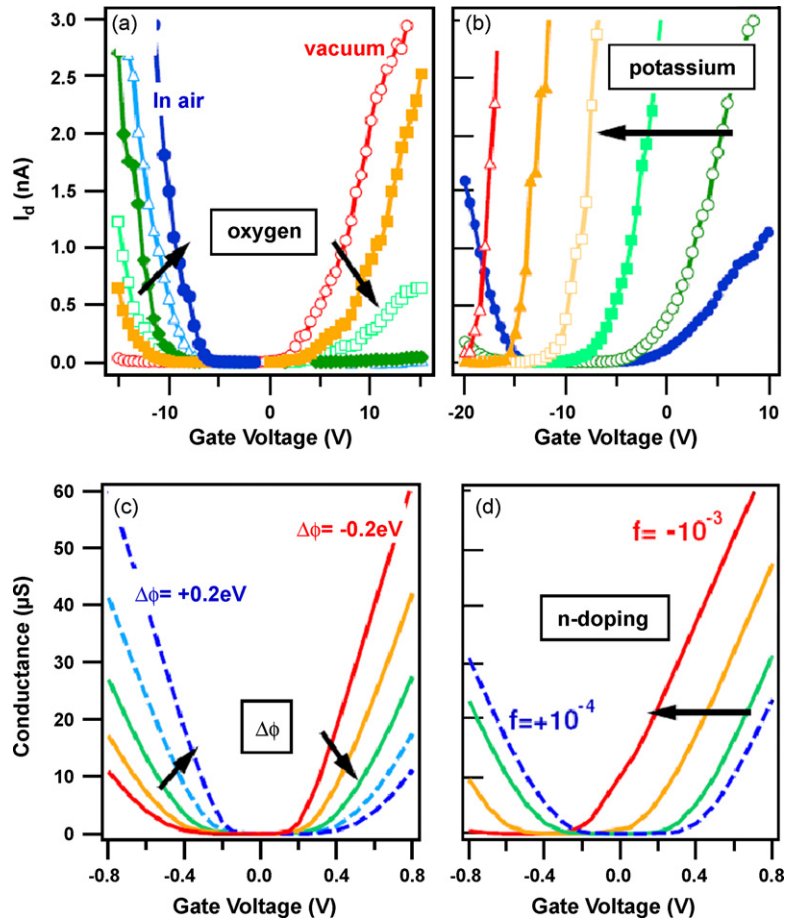


Fig. 5. Tests and simulations performed at IBM by Heinze et al. (a) Transfer characteristic change as a function of oxygen concentration. (b) Transfer characteristic change as a function of potassium doping level. (c) Simulation of the transfer characteristic change as a function of the metal work function change. (d) Simulation of the transfer characteristic change as a function of the doping level change [35].

this was not observed: the off bias interval was unchanged (Fig. 5). Starting from these observations, IBM researchers formulated the hypothesis that the gas molecules adsorption changed the value of the Schottky barrier built-up between the SWCNT and the metal in the contact region. To check this hypothesis, they simulated the effect on the CNTFET transfer characteristics caused by the change of the metal work function, as a consequence of the adsorption of oxygen. At the same time they simulated the effect of an “hypothetical” CNTFET oxygen doping. The results have been compared with the experimental ones and have unquestionably demonstrated the IBM hypothesis (Fig. 5).

In other studies performed by the same research team [36,37], it has been explained that the interaction of oxygen at the junction between the metal electrode and the SWCNT, changes the metal

work function and so the Fermi level alignment. The Fermi level at the contact is not pinned by “metal-induced-gap states” (MIGs), as it happens for contacts of most metals with usual semiconductors (Si, GaAs, ...), and it is controlled by the metal work function. In the light of this analysis, they have concluded that oxygen raises the metal electrode (Au in this case) work function and so it permits the switching of the electrical behaviour from n-type (in vacuum) to p-type in air (Fig. 6).

The IBM results were partly confirmed by researchers from CEA in France [38]. They fabricated CNTFETs with gold electrodes and exposed them to a vapour saturation dose of trifluoro-acetic Acid (TFA). Then they analyzed the transistor response evolution as a function of the desorption time of the TFA molecules. The aim of this work was to demonstrate that the Schottky barrier could be

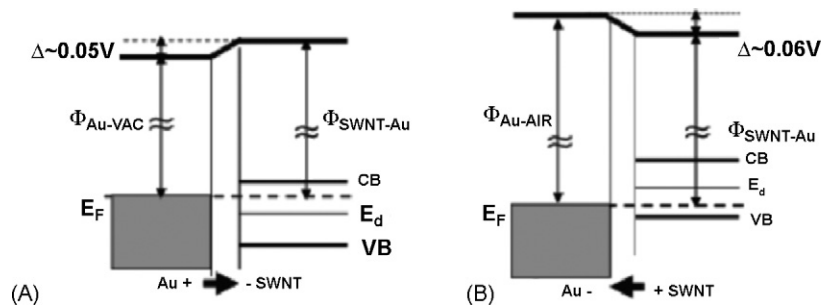


Fig. 6. Effect of Oxygen on the Fermi levels alignment: (a) Au/CNT contact in vacuum (n-type case), (b) Au/CNT contact in air (p-type case) [36].

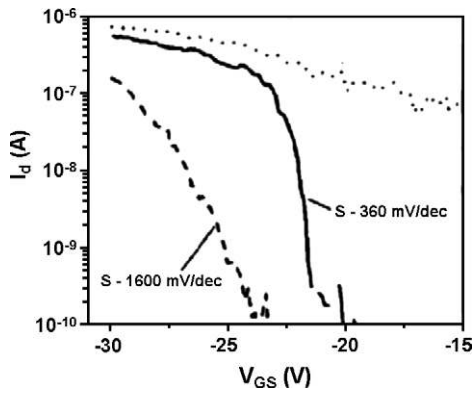


Fig. 7. Transfer characteristics of a CNTFET exposed to different concentrations of trifluoro-acetic Acid (TFA) obtained by Auvray et al. at CEA-Saclay: for high dose doping (dotted line), after TFA partial desorption (solid line), before exposure (dashed line) [38]. The subthreshold slope value is optimized for intermediate TFA concentrations.

specifically tailored in order to improve the transistor subthreshold slope ($S = dV_{GS}/d\log(I_{DS})$) using gas exposure (or chemical exposure in general). The initial hypothesis was that the effect of the TFA on the CNTFETs could be double:

- Doping the SWCNT (for extremely high concentrations).
- Changing the height of the Schottky barrier.

Indeed, if nanotubes are doped, a lateral shift of the V_{ON} , with no change of the S , has to be observed. On the opposite, if the Schottky barrier height is modulated at the metal/SWCNT contact (exactly as it has been achieved by the IBM team, changing the oxygen concentration) a sudden change of the S , without any shift of the off bias interval, should be obtained.

Their experimental results demonstrated that for very high concentrations, there was no effective control of the current driven by the gate voltage: this observation was consistent with a situation of highly p-doped channel. However, when the TFA started desorbing, they observed that the transfer characteristic and S of the CNTFET changed dramatically (Fig. 7).

The CEA team conclusion was that the TFA molecules were initially deposited on the SWCNT, on the oxide layer and on the metal/CNT contacts. As a consequence, the channel doping and the change of the S slope took place at the same time. After this initial phase, they observed the highest value for the subthreshold slope. This pointed out that vapour molecules desorbed more quickly from the tube than from the metal/SWCNT contact: the metal work function was increased by the TFA molecules dipole pointing towards the electrodes, reducing the barrier for holes. These remarks underlined that for the CEA team, the role of modulation of the metal/SWCNT Schottky barrier operated by the gas was the dominant effect. The doping effect was relevant only for abnormally large TFA concentrations.

The hypothesis of the gas effect on metal work function formulated by IBM researchers, and confirmed by the CEA team, can be explained using an analogy with the model developed for organic compounds and metal junctions [39,40]. In this case the interface is characterized by the presence of interface dipoles, which generate an electrostatic potential close to the electrodes. The presence of the interface dipoles at the contact modifies the energy of the electronic levels in organic compounds and the work function of the metal surface. When the interface dipole points its negative pole towards the organic film and its positive pole towards the metal, the result is an increase of both the metal work function and the highest occupied molecular orbital (HOMO) energy of the organic film, by addition of an electrostatic energy. Therefore, the hole injection

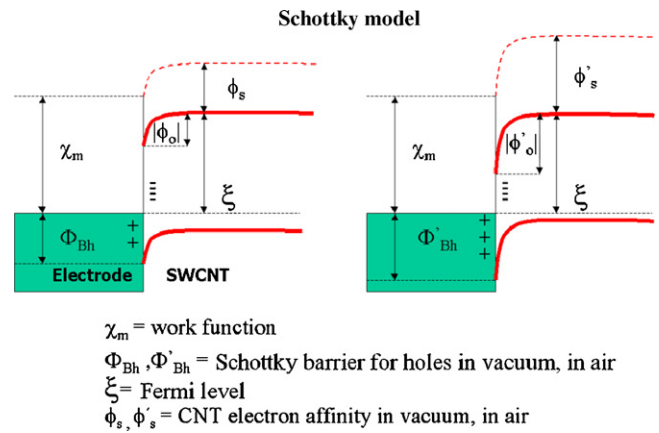


Fig. 8. Band diagram at metal/SWCNT (semiconducting) junctions in vacuum (left hand side) and exposed to air (right hand side) using the Schottky model [42].

barrier is reduced. On the other hand, when the dipole direction is reversed, the metal work function is reduced and so is the electron injection barrier. In the case of a metal/SWCNT junction, similarly, the gas molecules introduce electric dipoles at the interfaces and modify the intensity of the dipole pre-existing there.

This change directly influences the metal work function and the Fermi level alignment. This consideration totally agrees with the simulations and experimental results in the case of oxygen exposition obtained by IBM: changing the oxygen concentration, the dipole strength varies and the metal work function is increased, thus reducing the hole injection barrier (the hole current rises). The same interpretation can be made when the metal/SWCNT Schottky barrier is modulated using polar chemical compounds [38,40].

The IBM works have been analyzed and theoretically modeled by Yamada of NASA Ames Research Center [41,42]. Yamada has explained that the simple Schottky model cannot justify alone the effect of oxygen molecules on the modulation of the Schottky barrier value to obtain a p-type junction in air (Fig. 8). In fact, using the Schottky model, one assumes that the junction consists of an oxidized metallic electrode surface and a plain SWCNT or as a plain metallic electrode and an oxidized CNT, and therefore one proceeds in aligning Fermi levels at the contact. This analysis is based on two wrong assumptions. First, the gold surface is inert and so it does not interact with oxygen. Second, if one merely aligns the Fermi level at the contact, considering that the oxygen molecules are electronegative, they would increase the SWCNT electron affinity. Therefore, according to the standard Schottky theory one should obtain:

$$\Phi_{Bh} = E_G + \phi_s - \chi_m \quad (1)$$

$$\Phi'_{Bh} = E_G + \phi'_s - \chi_m \quad (2)$$

where Φ_{Bh}/Φ'_{Bh} , ϕ_s/ϕ'_s stand, respectively, for the Schottky barriers and the SWCNT electron affinities in vacuum and air, E_G is the SWCNT band gap and χ_m , the metal work function.

From these formulas, it can be deduced that an Au/SWCNT Schottky barrier should be lower in vacuum than if exposed to oxygen molecules because they are negatively charged. This is exactly the opposite of what has been observed by the IBM group. Yamada explains that the only way to consistently justify the effect of oxygen is to take into account a sort of transition region between the metal and the SWCNTs. This region is characterized by gold clusters on the electrode surface and charged oxygen molecules. The gold clusters are formed during the metal deposition on the SWCNT extremities. In fact, the gold atoms do not wet the SWCNTs and so clusters are first produced during Au deposition [43]. Yamada claims that in this zone the oxygen molecules can be chemisorbed on the clusters. Considering that oxygen molecules are negatively

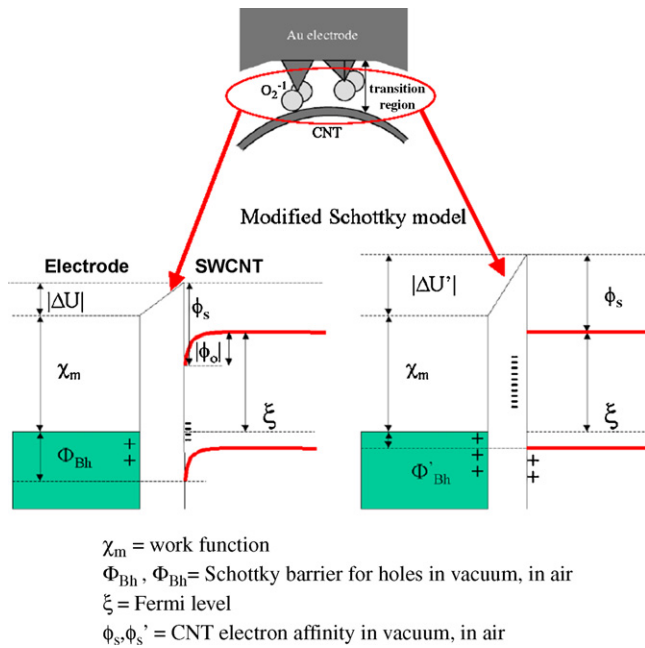


Fig. 9. Band diagram at metal/SWCNT (semiconducting) junctions in vacuum (left hand side) and exposed to air (right hand side) using the modified Schottky model [42].

charged, they induce a balancing positive charge in the metal and SWCNT. Consequently, a modification of the potential drop at the junction is observed (Fig. 9). This potential drop will be larger for CNTFETs exposed to air than in vacuum therefore:

$$\Phi_{Bh} = E_G + \phi_s - \chi_m - |\Delta U| \quad (3)$$

$$\Phi'_{Bh} = E_G + \phi'_s - \chi_m - |\Delta U'| \quad (4)$$

where $|\Delta U|$ and $|\Delta U'|$, respectively, stand for the potential drop in vacuum and in air. We can observe that in this case the Schottky barrier for hole in metal is lower if CNTFETs are exposed to air, according to the experimental results obtained by IBM researcher: the Yamada's model seems to be satisfying and suitable to describe the effective interaction of gases on metal/SWCNT junctions.

3. Effect of humidity on CNTFET

In the previous paragraph, we have seen that Kong et al. at Stanford invoked the presence of hydroxyl groups on the silicon dioxide surface. This explains why the water molecules present in ambient air have the tendency to be bound to the dielectric layer of CNTFETs. The first paper demonstrating their effect on the CNTFET performances was published in 2003 by Kim et al. at Stanford [44]. They showed that water molecules can shift the CNTFET transfer characteristics as a function of gate voltage variation (Fig. 10). They suggested that two types of water charge traps existed. The first type involves water molecules weakly adsorbed on the nanotube surface that can be easily removed by, e.g., pumping in vacuum. The second one involves water molecules bound on the SiO₂ dielectric surface near the nanotubes location. Therefore, in ambient air the thermally grown SiO₂ surface consists of Si–OH silanol groups that are hydrated by a network of water molecules, with one of their hydrogen atom bound to the silanols.

Sung et al. at Sejong University in 2006 [45] demonstrated that the second effect (i.e., water molecules bound near the nanotube location) was the most important. Indeed, simulating the effect of the hypothetic doping of the water molecules on SWCNTs, they concluded that physisorption of water molecules on SWCNTs cannot

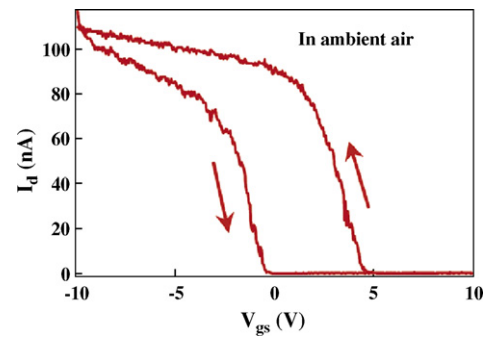


Fig. 10. Effect of Hysteresis on $I_d(V_{GS})$ for a CNTFET exposed to ambient air (measurements performed by Kim et al. at Stanford in 2003). The arrows show the gate voltage sense variation. Gate sweep rate 5.7 V/s, bias voltage $V_{ds} = 10$ mV, SiO₂ (dielectric layer) thickness = 500 nm.

explain the hysteresis on the transfer characteristics. They suggested that previous works demonstrating the opposite [46,47], were based on incorrect interpretations of the Mulliken analysis [48].

Mc Gill et al. at Florida State University, studying thoroughly the hysteresis caused by water molecules in 2006, demonstrated that this phenomenon could also be linked to the quality of the substrate used for device fabrication. In fact they set up a process to remove the water layer bound to the silanols on SiO₂ surface, using octadecyltrichlorosilane (OTS) functionalization of the dielectric layer [49]. Thus they were able to reduce strongly the hysteretic behaviour of the CNTFET but not to remove it completely when the gate voltage sweep interval was enlarged. They observed that the transfer characteristics shift due to hysteresis of a CNTFET with an OTS layer and one without it, were, respectively, in the positive and in the negative direction (see Fig. 11). The Florida State University team claimed that the phenomenon linked to these two behaviours were not the same. For the functionalized device, there is no effect due to water molecules but the shift is due to the presence of interface and bulk traps that can change their state with gate bias. These traps are strictly induced by the CNTFET fabrication steps.

Finally, although there are several works dealing with the effect of hysteresis on CNTFET transfer characteristics [50,51] we have not found in the literature systematic studies focused on the effect of different humidity concentrations on the electric response of CNT-FET based sensors.

We think that considering that hysteresis introduces a systematic error in measurements it will affect the final sensing measurements of the same amount, for a specific humidity concentration in ambient air (an offset voltage). Therefore, it is highly recommended to measure accurately the moisture level to achieve reproducible results for utilization in different environment conditions. Alternatively, differential measurements can be thought off, based on dedicated circuitry.

4. CNTFET based sensor using SWCNT mats

The previous paragraphs have dealt with CNTFET based sensors fabricated using individual SWCNTs. However, the utilisation of a single SWCNT presents some important issues. First, considering that no method up to now exists to fabricate only semiconducting SWCNTs, one cannot predict whether a SWCNT is metallic or semiconducting. Second, it is quite laborious to identify the position of one single SWCNT using fine observation methods such as atomic force microscopy (AFM). From an industrial point of view AFM is not a suitable solution for the mass manufacture of sensors. Third, considering that the CNTFET electrical characteristics are dependent on the single SWCNT physical characteristics (band gap in partic-

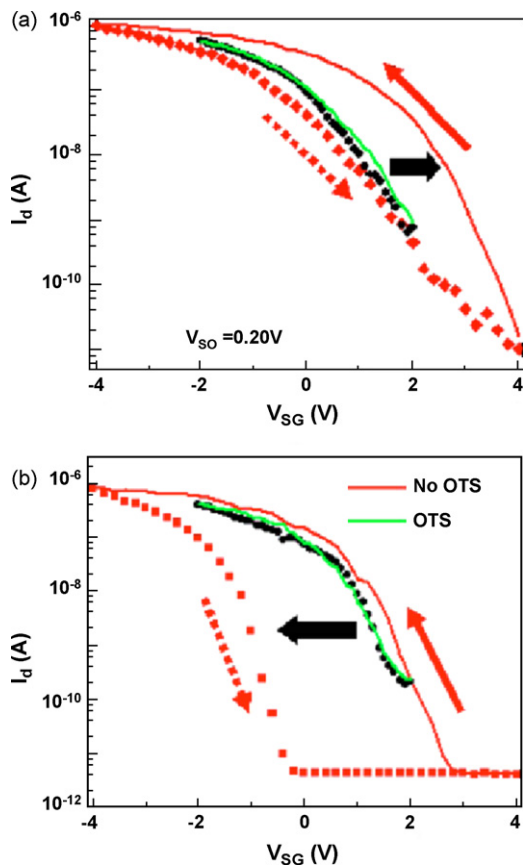


Fig. 11. Measurements performed by Mc Gill et al. at Florida State University in 2006 on the effect of dielectric layer charge trapping effect on final device hysteresis. (a) Transfer characteristics of a CNTFET (fabricated using Pd Electrodes) in a wide gate looping (red line) compared to its own hysteresis-free operation (black and green lines). The black arrow shows the threshold shift direction. (b) Transfer characteristics of a different hysteresis-free CNTFET compared to one fabricated without octadecyltrichlorosilane (OTS), ($V_{ds} = -0.1$ V).

ular, which depends on diameter for semiconductor specimens), it is very difficult to obtain reproducible devices.

Therefore, several research teams have focused their work on CNTFETs using SWCNT mats as channels. Indeed, as far as random networks are concerned, it has been shown that, through a percolation effect, an overall semiconductor behaviour could be obtained for carefully controlled areal densities [52–55].

Only two conditions must be fulfilled: the distance between the two electrodes must be larger than the SWCNT length (otherwise metallic nanotubes could cause a short-circuit) and the areal density of the SWCNT mat has to exceed slightly the percolation threshold for semiconducting specimens (remember that SWCNTs always come in mixtures of metallic (m) and semiconductor (s) specimens, with the approximate ratio $s/m = 2$; therefore, conditions can be found where the s-SWCNTs will percolate, whereas the m-SWCNTs will not, yielding an overall semiconductor behaviour). Actually, for too high densities, the conduction can reach an ohmic trend (the percolation of m-SWCNTs will short circuit the s-SWCNTs) with no gating effect [56]. It is noteworthy that the CNTFET devices achieved using this technique allow one to average the influence of each SWCNT on the final device characteristics making easier to obtain devices with highly reproducible electrical characteristics. However, even if the method employing SWCNT mats is very attracting, we have to recognize that the theoretical modelling of this kind of sensor is challenging. In fact, the physics of the interaction between the different SWCNTs in a chain must be studied deeper and also the effect of gases on these junctions.

Considering the extremely huge number of parameters, a lot of efforts will be necessary to define a suitable and quite complete model.

One example of CNTFET based sensor achieved using SWCNT mats, has been proposed by Snow et al. of the Naval Research Laboratory [57,58]. They fabricated a sensor using lithographically-patterned SWCNT networks between Ti drain and source contacts on a SiO_2 layer and Si substrate in a bottom gate configuration (Fig. 12). These sensors were exposed to saturated vapour of dimethyl-methyl-phosphonate (DMMP) [59] which is a nerve agent simulant. They found a V_{ON} negative shift, compared with results obtained in ambient air. The phenomenon was explained as a consequence of the electron transfer from DMMP to the SWCNTs (gas “electron-donating” behaviour). The observed recovery time was of several hours of exposure to ambient air, but could be dramatically reduced simply applying a reverse bias for around 200 s (Fig. 13). Researchers thought that the Coulomb interaction between the DMMP and the negative charges induced in the channel by the gate voltage (positive), reduces the desorption barrier.

The same method has been employed by researchers at Yonsei University in South Korea [60] for refreshing CNTFET based sensors after exposure to 300 ppm of NO_2 and NH_3 in vacuum (the carrier gas and the humidity concentrations are not specified in the paper). In this case the CNTFET gate voltage was inverted for 30 s: a negative voltage to enhance desorption of NO_2 gas molecules and a positive gate voltage for NH_3 gas molecules. This technique is very interesting because it does not induce any sensor degradation (e.g., heating several times) and it provides a room temperature refreshable sensor (low power consumption device).

Another CNTFET sensor obtained using SWCNT mats has been tested at Sungkyunkwan University in South Korea. Jeong et al. [61] fabricated CNTFET depositing SWCNT diluted in dichloroethane (DCE), using a solution-casting process, between Mo based electrodes with a distance of $5 \mu\text{m}$. The dilution was optimized in order to achieve a uniform, reproducible SWCNT distribution with a high-controlled areal density. The researchers tried to evaluate the sensitivity (defined as the ratio between the difference of the resistance after and before exposure, to the initial one) of the CNTFET based sensors as a function of the initial FET resistance. They found that for NO_2 sensing (between 200 and 1500 ppm, the carrier gas and the humidity concentrations are not specified in the paper) the highest initial resistance CNTFETs had also the highest sensitivity. To explain this phenomenon, they formulated the hypothesis that a reasonable high initial resistance limits the dark current and so enhances the final sensitivity. This is justified by a too high-density mat that gives rise to a too low initial resistance value (the probability of having metallic chains connecting the two electrodes is high) and so reduces the relative change after gas adsorption. From another point of view, this phenomenon can also be explained considering that metallic chains are not sensitive to gas adsorption (they do not build up a Schottky barrier with the metal electrodes) and so gas molecules have a limited influence on the final change of the CNTFET transfer characteristic, as it has been shown by other groups [62–65].

Finally, an integrated sensor based on CNTFET transistors has been manufactured by researcher from the NASA Ames Research Centre [66]. They fabricated a device composed of interdigitated Pt electrodes (with finger distance ranging from 4 to $50 \mu\text{m}$) with carbon nanotubes chains, grown using an in situ chemical vapour deposition process (CVD) [67], as the transistor channel. This final device, composed by twelve CNTFETs, shows a very interesting sensitivity for NO_2 and NH_3 concentrations, respectively, between 400 ppb and 10 ppm, 4 and 50 ppm in air (the humidity concentration is not specified in the paper). The great originality of this microsystem consists in an embedded heating layer situated between the substrate and the dielectric layer (Si_3N_4). This heater



Fig. 12. CNTFET fabricated by Snow and co-workers at NRL in 2003 [57]. (A) Optical image of a CNTFET: Ti contacts were evaporated on top of a SWCNT film grown on thermal SiO₂. Channel was 10 μm long. The Si substrate serves as a back gate. (B) Representative AFM image of a SWCNT network that shows multiple conduction pathways via interconnected CNTs.

could be used to reduce the recovery time, desorbing more rapidly the gas molecules (Fig. 14). This microsystem is particularly interesting because it allows one to identify the principal problem to be solved when moving from a lab prototype to a device for real life applications, introducing at the same time some solutions for the final packaging.

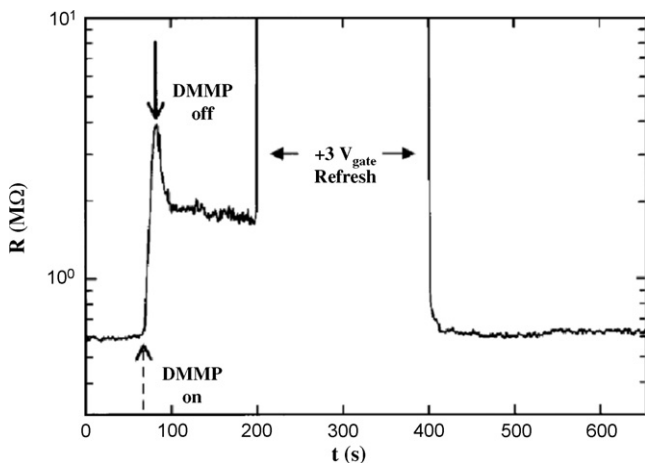


Fig. 13. Effect of the bias gate inversion on the resistance change of a CNTFET channel achieved using SWCNT networks after exposure to DMMP (Snow and co-workers at NRL in 2003 [57]).

Considering all these examples, it is not clear whether the sensing mechanism in a mat is still due to the interaction of gas species with metal/SWCNT junctions or with the SWCNTs mat itself, *i.e.*, with m-SWCNT/s-SWCNT junctions. Indeed, the scientific teams working on SWCNT mat devices, took a pragmatic point of view, focusing their efforts on results and so far, they did not try to study deeper the physics phenomenon behind.

We consider that also in the situation of devices fabricated using SWCNT mats, the main phenomenon, at least for channel lengths below 100 μm, is the interaction of gas with Metal/SWCNT junctions. Several considerations allow us to support this hypothesis.

We can observe that in CNTFETs fabricated using SWCNT mats, three types of electric contacts can be identified:

- Those between two semiconducting SWCNTs.
- Those between two metallic SWCNTs.
- Those between one metallic and one semiconducting SWCNT.

Considering the works performed by Fuhrer et al. [68–70] at the University of California at Berkeley we know that the contact resistance between two SWCNTs having two different electronic characters is larger than the contact resistance between two semiconducting or metallic SWCNTs. This is due to the fact that the total charge transmission probability between two SWCNTs with different electronic character is obtained from two factors: the transmission probability of tunnelling between two SWCNTs (through the so-called “voltage drop zone” [41–42])

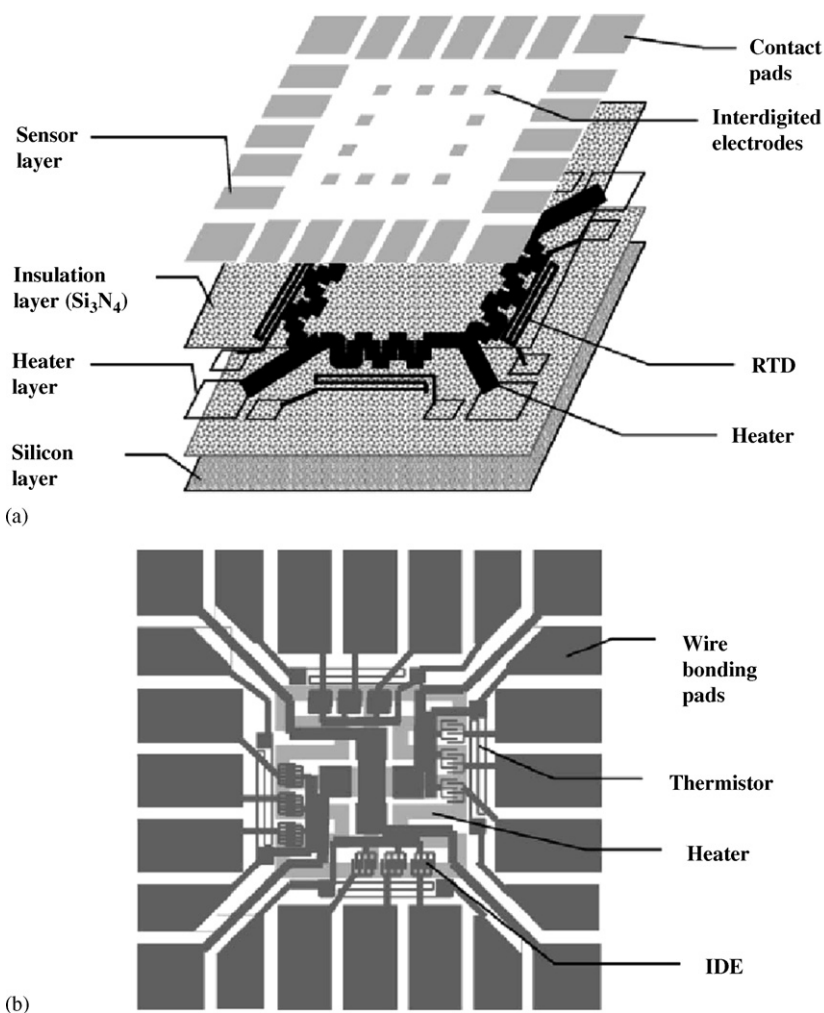


Fig. 14. Schematic view of the different layers composing the integrated sensor developed by Li et al. at NASA Ames Research Center in 2005 [66].

and the transmission probability of the tunnelling through the Schottky barrier when it exists (contact between a metallic and a semiconducting nanotube). The result is a contact resistance two orders of magnitude larger for heterogeneous contacts [68–70]. The main consequence is that the current will preferably flow in chains composed by entirely semiconducting or metallic SWCNTs.

Therefore, if we suppose that after exposure to a gas, there will be a change of the height of the Schottky barrier at the contact between two SWCNTs with a different electronic character, this change will not influence the current flowing in the mat. Moreover, the contact between two SWCNTs with the same characters will not be influenced by the gas considering that the Fermi Levels in the SWCNTs will stay aligned (they will move of the same amount of energy, compared to vacuum level).

The conclusion is that the metal workfunction change at the contacts between metal and SWCNT will be the main phenomenon to perform gas sensing using CNTFETs fabricated with SWCNT networks (for devices with their channel length below $100\ \mu\text{m}$). However, considering the literature on the domain, up to now, no scientific team has performed measurements (exposing the device to gas after covering alternatively the metal/SWCNTs contacts and the whole CNTFET) confirming this hypothesis.

As quoted above, if we assume that the contact resistance between two SWCNTs changes after being exposed to a gas, this change will be negligible if the channel transistor is short ($<100\ \mu\text{m}$). In fact, the metal/SWCNTs contact resistance is around

three orders of magnitude larger than the resistance between two SWCNTs with the same electronic character. Therefore, its influence on the final sensing will be predominant. This predominance will be theoretically strongly reduced using long channel transistors ($\sim 100\ \mu\text{m}$). If we fabricated transistors channel composed by networks of nanotubes with a number of SWCNT/SWCNT contacts in each chain linking the two electrodes larger than 100, in this case the mat resistance will attain a value comparable to the metal/SWCNT contact resistance.

Exploiting this idea, Snow et al. at NRL in Washington in 2005 [72], fabricated a sensor with a channel length of $340\ \mu\text{m}$ and were able to detect 2 ppm of DMMP. In order to enhance dramatically the mat sensitivity influence to low concentrations, Perkins and co-workers of the same research team in 2006 [73] proposed to create defects on the SWCNT walls in a mat (by exposure to ultraviolet light (UV)/ozone followed by a soak in peroxide solution).

This approach can be very interesting but considering that it strictly concerns conductance measurements and not transistors devices, it is not in the focus of this paper. Therefore, we will not develop it further. This will be also the case of sensing using capacity measurements [72].

5. Routes to improve selectivity

We have shown in the previous paragraphs that CNTFET based sensors can be very sensitive to gas molecules exposure. However, the real issue remains to demonstrate a suitable selectivity.

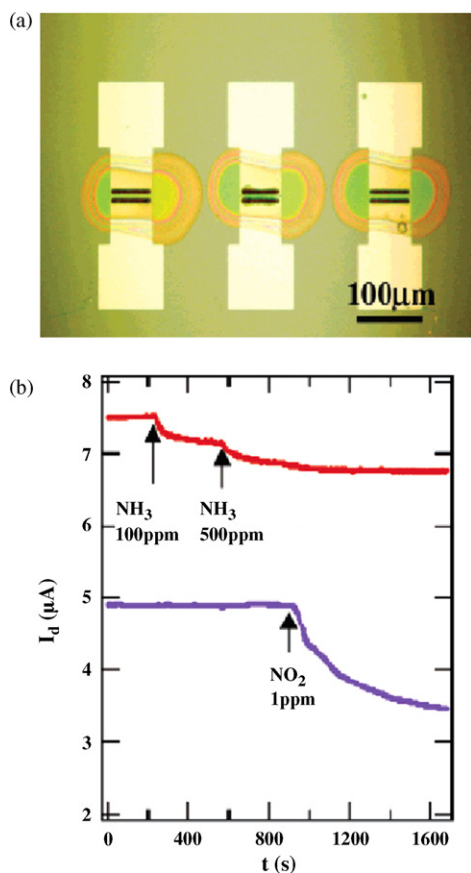


Fig. 15. Selective sensing performed by Qi et al. at Stanford in 2003, using an array of functionalized CNTFETs. (a) Optical image of CNTFETs functionalized using micro-spotting technique. (b) Experimental results for CNTFETs functionalized with PEI (violet solid line) and with Nafion (red line) after exposure to NO₂ and NH₃ [71]. Gas concentrations are reported on the graph. Air was the carrier gas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Their approach consisted in fabricating an array of functionalized CNTFETs: the devices were covered by specific polymers to enhance sensitivity to a specific gas as well as selectivity (Fig. 15). This technique echoes the functionalization technique already used with surface acoustic wave (SAW) filter devices for gas sensing [74,75] and it has also been used for sensors based on SWCNT networks developed by Nanomix Inc., for CO₂ sensing [76,77]. The aim of the Stanford team was to demonstrate that these polymers could allow one to detect selectively different gas species in the presence of interfering gases. The CNTFETs were fabricated by bridging Mo electrodes with SWCNTs obtained by in-situ CVD growth on a SiO₂/Si substrate [78]. First the CNTFETs were functionalized using polyethyleneimine (PEI) simply by immersion. Following the PEI functionalization, a sudden change of CNTFET electrical character was observed: they switched from p-type to n-type. This behaviour is linked to the doping effect of high-density amine from the on PEI molecules [79] on nanotubes. Concerning the physical interpretation of the phenomenon, the effect of polymer on CNTFETs was explained by the doping of nanotube and not by the modulation of the Schottky barrier. Concerning the results after exposure, the PEI coated CNTFETs showed an extremely higher sensitivity to NO₂ compared to bare CNTFETs (Fig. 16): the CNTFET sensors could detect a concentration of 100 ppt, and saturated at 3 ppb. This value of 100 ppt constitutes up to now the lowest gas concentration ever detected by a CNTFET gas sensor.

This effect was explained, as before, by the reduction of the electrons number in the channel, and of the conductance, caused by

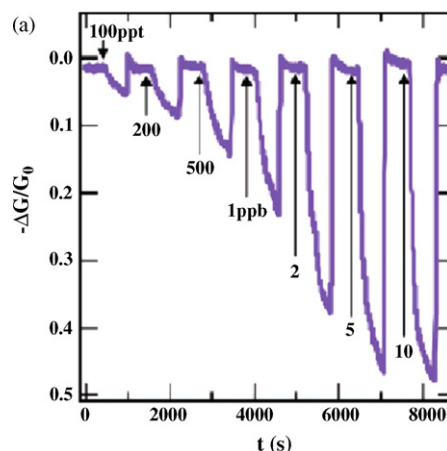


Fig. 16. CNTFET PEI functionalized resistance change as a function of time. Desorption is achieved using UV light [71].

NO₂ which is a strong “electron-withdrawing” gas specie. Concerning the exposure to interfering gases, the functionalized CNTFETs showed no transfer characteristic change after exposure to NH₃ (up to 1000 ppm), CO, CO₂, CH₄, H₂ and O₂.

In the second part of their study, the Stanford team functionalised a CNTFET array using Nafion, deposited by micro-spotting. The objective was to reduce the sensor sensitivity for “electron-donating” gas species. In this case, the sensors showed a good sensitivity for concentrations between 100 and 500 ppm of NH₃ but no response to 1 ppm of NO₂. No further results for higher NO₂ concentrations are given in the paper.

The Stanford team employed a new approach for rapidly desorbing gas molecules: they refreshed the sensors using UV light illumination [80]. This approach has also been patented [81]. From our point of view, this solution is attractive but some concerns can be raised. Polymers are highly sensitive to environment moisture and are the principal cause of the high false alarm rate observed for polymer-functionalized gas sensors based on SAW filter. Moreover, the integrity of the polymer layer after several UV exposures, will have to be assessed.

Finally, we point out that polymer encapsulation will force the molecules under investigation to diffuse through them, which will increase the response and recovery time of the sensor. A good example of this behaviour is given in Ref. [32].

Another example of utilization of CNTFET functionalization to improve sensitivity and selectivity has been shown by researchers from the University of Pennsylvania [82,83]. They chose the “bio-functionalization” route, using several DNA sequences. In more details, they functionalized in situ grown SWCNTs, bridging two gold electrodes and exposed the CNTFET array to different vapours: methanol, propionic acid, trimethylamine (TMA), dinitrotoluene (DNT) and DMMP (Fig. 17).

They found that the DNA decorated CNTFETs had an enhanced sensitivity (Table 1). However, they found this enhancement dependent on the DNA sequence used for a specific gas sensing. These results made them researchers think that using a large array of CNTFETs functionalized using “ad-hoc” DNA sequences, could permit to obtain a sort of electronic nose to identify univocally a large number of chemical and biological targets. However, up to now, the physical phenomenon at the basis of this dramatic sensitivity enhancement has not been completely understood and no clear interpretation has been advanced.

Another approach to improve selectivity is to diversify the CNTFET metal electrodes. This concept has been developed by the present authors, members of the joint research team Thales/Ecole Polytechnique in France (Nanocarb Lab.) [84–87]. More precisely,

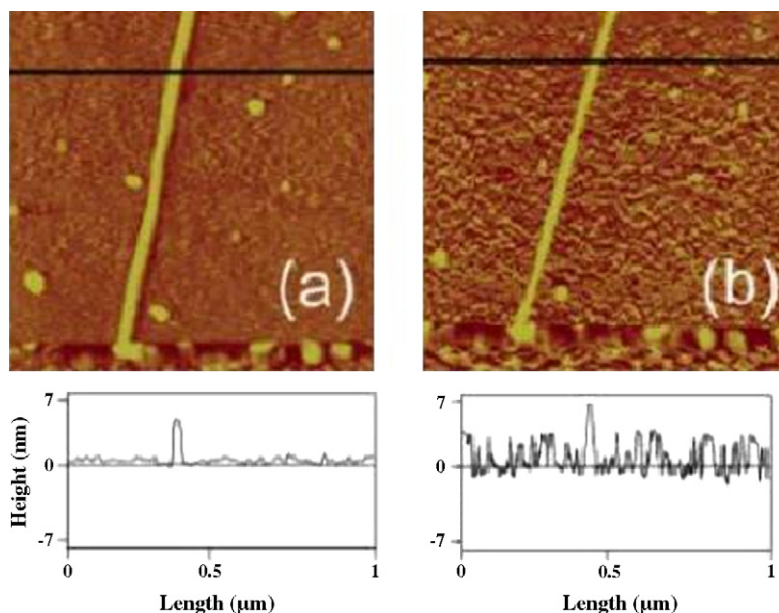


Fig. 17. DNA SWCNT functionalization performed by Staii et al. at Pennsylvania University in 2005: AFM images and line scans of the same SWCNT before (a) and after (b) DNA functionalization [82].

Table 1

Source/drain current change after exposure to different analytes for a CNTFET functionalized using two different DNA sequences [82].

| Odor | Vapour pressure (Torr) | Estimated concentration (ppm) | % $\Delta I/I$ | | |
|----------------|------------------------|-------------------------------|----------------|--------------|--------------|
| | | | Bare swCN | swCN + Seq 1 | swCN + Seq 2 |
| Water | 17.5 | 700 | 0 ± 1 | 0 ± 1 | 0 ± 1 |
| Propionic acid | 4 | 150 | 0 ± 1 | $+17 \pm 2$ | $+8 \pm 1$ |
| TMA | 500 | 20000 | -9 ± 2 | -20 ± 2 | -30 ± 2 |
| Methanol | 100 | 4000 | 0 ± 1 | -12 ± 2 | -20 ± 2 |
| DMMP | 0.6 | 25 | 0 ± 1 | -14 ± 2 | -7 ± 2 |
| DNT | 1 | 40 | 0 ± 1 | -14 ± 4 | -4 ± 2 |

we exploited the modulation of the metal work function induced by gas exposure, in order to get the fingerprinting of a particular gas using a network of CNTFETs. These were fabricated using different metals for the contacts: taken altogether, the change of transfer characteristics of a transistor array after exposure to a particular gas can identify it unambiguously (Fig. 18). This idea was also intro-

duced by G. Gang of Molecular Nanosystem Inc. in 2002 even if the concept of network, for gas fingerprinting, had not been developed [88]. As a proof-of-concept, we manufactured CNTFETs composed by four different metals as electrodes: Au, Pd, Pt and Ti. The work functions for these metals are, respectively, 5.1 eV for the first two, 5.65 eV and 4.33 eV for the two last ones [89–93]. We used these

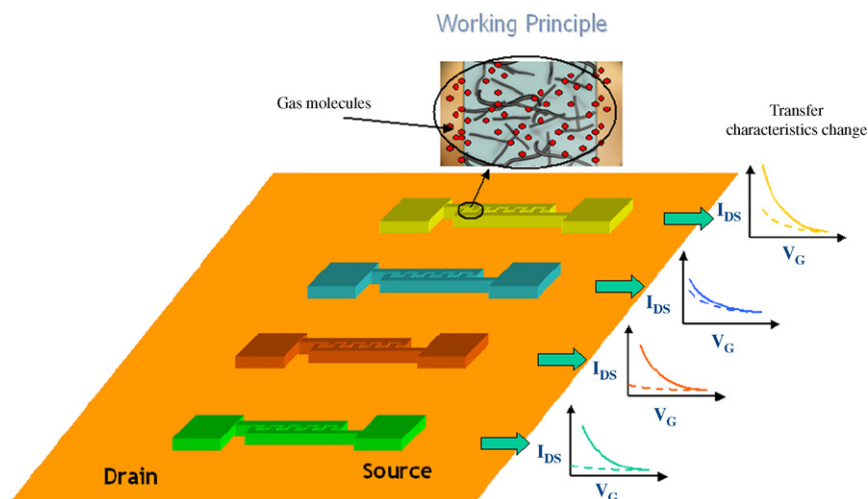


Fig. 18. Schema of the working principle of the gas sensor device system developed by Ecole Polytechnique and Thales [74]: an array of four CNTFETs achieved using interdigitated electrodes composed of different metals. Each colour corresponds to a different metal. On the right the corresponding relative CNTFET transfer characteristic changes before (solid lines) and after (dashed lines) gas exposure. In the inset, a detail of two electrodes fingers and of nanotubes chains linking them.

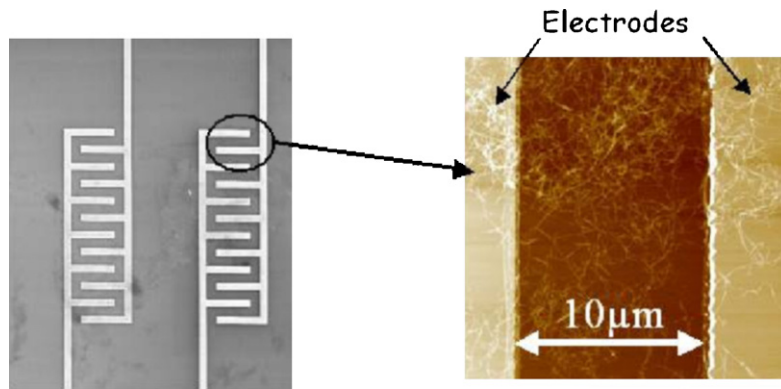


Fig. 19. Left-hand side: SEM image of interdigitated CNT transistors fabricated at Thales Research and Technology in 2006 [86]. Right-hand side: AFM detail of carbon nanotubes random network between two electrodes.

Table 2

Summary of the results and number of transistors tested for each different metal electrode.

| Current reduction after DMMP exposure | |
|---------------------------------------|--|
| Metals | I_{DS} current reduction % after exposure (1 ppm DMMP) error $\pm 5\%$ |
| Ti/Pd | 90 |
| Ti/Au | 65 |
| Ti | 50 |
| Ti/Pt | 20 |

metals in order to check whether the gas interaction was related only to the initial work function of a metal or if it depended on the nature of gas and electrode interaction.

We performed several measurements using different electrode designs (20 transistors for each metal with different electrodes distance (Fig. 19)) and these results were in close agreement with the initial hypothesis: it seemed that the sensor sensitivity was not influenced by the number of nanotubes linking the electrodes. The results obtained after exposure of CNTFET transistors to 1 ppm of DMMP in ambient conditions are shown in Table 2. From these measurements, researchers formulated the hypothesis that differ-

ent metals interact in a different way with the DMMP. The result showing that the Pd and Au transfer characteristic change was very different is particularly interesting, since these two metals have the same work function. This seems to confirm that the effect of gas on CNTFET characteristics was not simply related to the initial metal work function but probably to a specific chemical interaction between the metal and the gas: apparently the DMMP molecules influence the metal work function in a specific way and so the electric response of the transistor. New measurements are in progress to confirm these results.

Another interesting approach has been developed by researchers at Nanomix Inc. and Pittsburgh University. They exploited an idea first introduced in 2001 by Kong et al. of Stanford University [94]: to decorate the SWCNTs constituting the channel of a CNTFET with metal nanoparticles. They deposited nanoparticles of different metals on networks of SWCNTs connecting two Pd electrodes (Fig. 20). Therefore, they fabricated an array of CNTFETs each one being characterized by a different metal “decoration” [95,96]. They exposed this array to several gases (NO [92], H₂, CO, CH₄, H₂S, NO₂, NH₃ [96]) and they observed a specific change of the transfer characteristics of each transistor as a function of the nature of the nanoparticles and of the gas. These results made researchers think them that large array of “metal-decorated” CNTFETs could

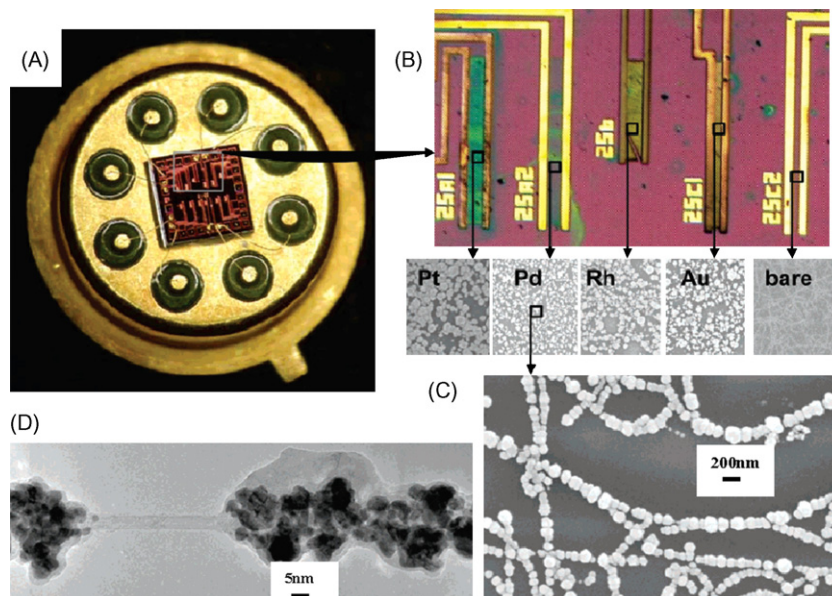


Fig. 20. CNTFET based sensor chip developed by Starr et al. at Nanomix Inc. [95], (a) optical image of the sensor chip on a TO-type header. (b) Array of CNTFETs decorated using different metals. (c) SEM image of CNT with metal particles on their surfaces. (d) HRTEM image of Pd decorated CNTs.

be used in order to recognize univocally any gas, identifying its electronic fingerprinting.

Regarding the physics of the phenomenon, researchers from the Stanford team, who had analyzed the electrical behaviour of one CNTFET decorated with Pd nanoparticles after exposure to H_2 , stated that the H_2 dissociated on the Pd surface lowered the Pd work function. This reduction gave rise to an increase of the contact Schottky barrier for holes thus reducing the channel conductance of the p-type device. This hypothesis could explain the experimental results for H_2 but could not be applied for other gas species.

Kauffman and Starr [96] failed to try an exhaustive explanation for the phenomenon but underlined the main difference between the interaction of metal nanoparticles/SWCNTs and metal electrodes/SWCNTs. In the first case without any molecular interaction (exposure to gas), the nanoparticles acted exactly as inert hole scattering sites, reducing mobility. Only upon molecular interaction, electronic interaction between NO and the metal nanoparticle creates added electronic density on the metal, which after crossing a small potential barrier results in electron-hole recombinations creating a negative shift in the device gate voltage. In this case the

metal nanoparticle/SWCNTs junctions could be described using the Yamada model, introduced previously.

A very different approach to carry out with success selectivity has been proposed by researchers at Yonsei University in South Korea [60]. As quoted in the previous paragraph, they obtained refreshable sensors inverting the polarity of the gate voltage after NO_2 and NH_3 gas exposure. Indeed, they pushed more deeply their analysis and observed that the rate of desorption of the gas molecules was dependent on their nature. They observed that after exposure to 30 and 300 ppm of NH_3 and after refreshing the CNTFET based sensor applying a gate voltage of 10V (to accelerate gas desorption), the slope of the I_{DS} as a function of time (decay rate) was the same in both cases (-0.1 nA s^{-1}) and was due to the concentration but only to the gas type. After having exposed the same device to ethanol (1000 ppm) and benzene (15 ppm), they obtained, after refreshing at the same voltage, different decay rates: -0.07 nA s^{-1} for ethanol and -0.04 nA s^{-1} for benzene (see Fig. 21). These results made them think that the decay rate could be used to perform selective measurements of the gas species considering that this time interval is univocally related to the binding energy of the adsorbed molecules.

6. Conclusions

In this paper we have exposed different recent studies dealing with gas sensors based on CNTFETs, whether made with individual SWNTs or with random SWNT networks (mats). The main sensing mechanism seems to be the modulation of the Schottky barrier height at the contacts, due to the build-up of interface dipoles that depend on the gas specie, but also on the chemical reactivity of the metal constituting the source and drain electrodes. The “wetting” of the contact metal on the nanotubes is also a parameter to take into account in the sensing mechanism, since it can shape the interface, leading to the formation of a transition region of paramount importance.

Devices based on mats show very promising performances for striking the sensor market in the next years. Numerous advantages can be advanced: extreme sensitivity (down to 100 ppt for NO_2), very short response and recovery times (some seconds), good efficiency at room temperature, low power consumption, CMOS compatibility (relatively low cost). One of the major problems now is to get a higher selectivity compared to other existing gas sensor technologies. Different routes to improve selectivity, have been proposed. They are based on the diversification of metal electrodes, polymer functionalization, metal particle decoration of the SWCNT mat, time desorption resolution. Common to all these approaches is the tendency to multiply the number of measurements using different sensor parameters (the metal electrodes nature, the functionalising polymers, the metal particles on the mat, ...), in order to develop a matrix or an array of CNTFETs that will allow one to identify accurately the “signature” of a particular gas. This seems to be the most viable route to achieve highly selective devices.

Moreover, the theoretical efforts for an in depth understanding and modelling of the interaction of gases with CNTFETs (obtained using a single SWNT or a mat) must be enhanced. For example, the effect of gases on polymer- or DNA-functionalised CNTFETs or on metal electrodes is not yet completely clear.

Finally, other technological hurdles must be overcome in order to bring these sensors out of research laboratories: the design and fabrication of suitable driving circuits (particularly for arrays of CNTFETs), the stability of the sensor response during long periods of time, the influence of humidity, etc.

Last but not least, other nanomaterials such as semiconductor or oxide nanowires could also be used in the future as active materials for gas sensing [97].

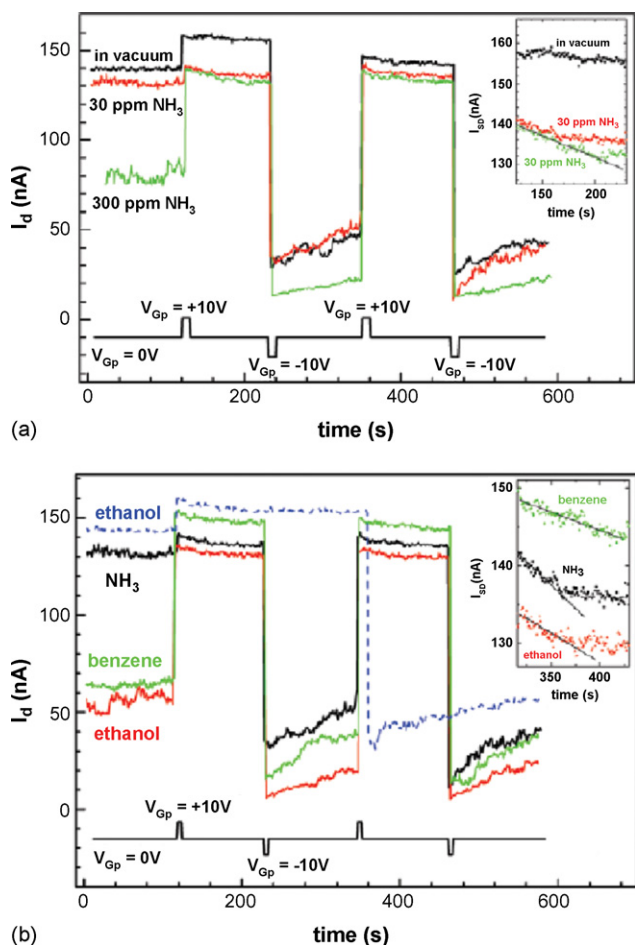


Fig. 21. Measurements performed by Chang et al. at Yonsei University (South Korea) in 2007 describing the dynamic of gas desorption on CNTFET achieved using SWCNT networks. (a) Effect of inverting the gate voltage on the gas desorption of NH_3 for different concentrations (30 and 300 ppm). In the bottom of the picture, the gate voltage as a function of time. In the inset a detailed view of the current as a function of the decay time: the decay rate of NH_3 does not depend on the concentration of the gas. (b) Effect of inverting the gate voltage on the gas desorption of NH_3 , benzene and ethanol. In the bottom of the picture, the gate voltage as a function of time. In the inset the different decay rate as a function of the gas: each gas has its specific decay rate [60].

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Biographies

Paolo Bondavalli was awarded his PhD from the National Institute of Applied Sciences of Lyon in 2000. His thesis dealt with MicroOptoMechanical Systems (MOEMS) for gas sensing. The same year, he joined Thales Laser Diodes (TLD) research and development team where he worked on developing micropackaging and test facilities for power laser diodes. He moved to Thales Research and Technology (TRT) in 2001 where he joined the MEMS Microtech team. He was in charge of the micropackaging design of MEMS RF devices. He joined the NANOCARB Laboratory in TRT during 2004. His research deals with carbon nanotubes gas sensor, Silicon nanowires based sensors for biological detection, thermal management using CNT. He is the author and coauthor of 20 scientific papers dealing with MOEMS, MEMS RF, CNTFET based sensors and of several patents dealing with gas sensors and thermal management through CNTs. He is EC expert in FP7 framework, and National French Agency expert.

Pierre Legagneux was awarded his PhD from the University of Orsay in 1989 and joined the Central Research Laboratory of Thomson-CSF which is now Thales Research & Technology. His research interests include the design and fabrication of nanotube and nanowire based devices for electronic applications. He was the coordinator of two European projects which relate to the study of nanotube for field emission applications (Nanolith and Canvad). P. Legagneux is the author/co-author of more than 60 papers and 15 patents including 6 on nanotube based devices. He is the head of Nanostructures Laboratory at Thales R&T.

Didier Pribat graduated from Grenoble University in 1977. He worked for 23 years within the Central Research Laboratory of Thomson-CSF (now Thales Research & Technology) on various subjects of materials science and semiconductor technologies (heteroepitaxy, solid electrolytes, III–V materials and devices, . . .). In 1991 he started a group on Large Area Electronics and has been particularly involved in low temperature polysilicon technology, including polysilicon synthesis by excimer laser crystallisation, thin film transistors (TFT) fabrication, characterisation and modelling, as well as circuit design and simulation. He joined CNRS/Ecole Polytechnique in 2001 and started the activity on carbon nanotubes for molecular electronics. He is currently Director of the Technology Transfer Office of Ecole Polytechnique and expert to the EC and the EPSRC (London). D. Pribat has published or presented more than 150 papers. He is also co-author of two book chapters and author or co-author of more than 50 patents.