DOI: 10.1002/cphc.200900743

Graphene on Au(111): A Highly Conductive Material with Excellent Adsorption Properties for High-Resolution Bio/Nanodetection and Identification

Bo Song,[a] Di Li,[a] Wenpeng Qi,[a] Marcus Elstner,[b] Chunhai Fan,*[a] and Haiping Fang*[a, c]

Based on numerical simulations and experimental studies, we show that a composite material which consists of a sheet of graphene on a Au(111) surface exhibits both an excellent conductivity and the ability to stably adsorb biomolecules. If we use this material as a substrate, the signal-to-noise ratios can be greatly enhanced. The key to this unique property is that graphene can stably adsorb carbon-based rings, which are widely present in biomolecules, due to π-stacking interactions while the substrate retains the excellent conductivity of gold. Remarkably, the signal-to-noise ratio is found to be so high that the signal is clearly distinguishable for different nucleobases when an ssDNA is placed on this graphene-on-Au(111) material. Our finding opens opportunities for a range of bio/nano-applications including single-DNA-molecule-based biodevices and biosensors, particularly, high-accuracy sequencing of DNA strands with repeating segments.

1. Introduction

The electric conductivity of bio single molecules is of great importance not only for observing/detecting their conformations, concentrations and electronic structures, but also for a variety of nanoscale applications, including biosensor, biochip and scanning tunneling microscopy (STM) based DNA identification.[1–10] Very recently, Dong and co-workers reported a chemically reduced graphene oxide modified glassy carbon, which can be applied as a more robust electrode for the preparation of an electrochemical sensing and biosensing platform.[11] Nevertheless, such important applications are often hindered by the presence of large noises, leading to low signal-to-noise ratios. This is partly due to the absence of materials which have both an excellent conductivity—inducing large electric signals—and a good adsorption to biomolecules to induce strong substrate–molecule coupling, which greatly reduces noise.

The existing materials with excellent conductivity, such as gold (which has been widely used in experiments and measurements), usually tend to exhibit a poor tendency to adsorb biomolecules, which results in weak substrate–biomolecule coupling, thereby inducing a large noise.

Recently, single-sheet graphene and graphene nanoribbons have been fabricated, while many studies and applications mainly concentrate on its special electronic structure and conductivity of graphene, such as on its good conduction in the parallel direction.[12–17] We notice that graphene has another very important property resulting from its special molecular structure: it usually strongly adsorbs to biomolecules[18] due to the π-stacking interactions[19] between its hexagonal cells and the carbon-based ring structures widely present in bio/nanomolecules. This has been demonstrated by recent experiments that charge can be transferred through ssDNA to graphene due to the adsorption of ssDNA on graphene.[20]

Very recently, graphene on SiO_2[21] and graphene deposited on thin nickel layers[22] were successfully prepared by the groups of Dai and Hong, respectively. Song et al. experimentally achieved the transfer printing of graphene using a gold film.[23]

Herein, based on numerical simulations and experimental studies, we show that a perfect graphene sheet with a gold surface underneath it exhibits both an excellent conductivity and the ability to stably adsorb biomolecules. When using this material as a substrate, the signal-to-noise ratios are greatly enhanced. We find that the key to this unique property lies in that the graphene can stably adsorb carbon-based rings that widely exist in biomolecules, while the graphene-on-Au(111) material retains the excellent conductivity of gold. Remarkably, the signal-to-noise ratio is found to be so high that the resonant currents are clearly distinguishable for different nucleobases when an ssDNA is placed on this graphene-on-Au(111) substrate. Our finding opens opportunities for a range of bio/nano applications including DNA-based biodevices and biosen-

[a] Dr. B. Song, Dr. D. Li, W. Qi, Prof. C. Fan, Prof. H. Fang
Laboratory of Physical Biology, Shanghai Institute of Applied Physics
Chinese Academy of Sciences, P.O. Box 800-204
Shanghai 201800 (China)
Fax: (+86) 21-59553021
E-mail: fchh@sinap.ac.cn
fanghaiping@sinap.ac.cn

[b] Prof. M. Elstner
Institute of Physical Chemistry, University of Karlsruhe
D-76131 Karlsruhe (Germany)

[c] Prof. H. Fang
Theoretical Physics Center for Science Facilities (TPCSF), CAS
19(B) Yuquan Road, Beijing 100049 (China)

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/cphc.200900743.

sors, particularly, high-accuracy sequencing of DNA strands with repeating segments.

2. Results and Discussion

Previous investigations by first-principle-based approaches[24] showed that Au nanoclusters can be stably adsorbed onto the graphene sheet and that van der Waals forces play a key role in the interactions between these gold nanoclusters and the graphene sheet. Our 1 ns molecular dynamics (MD) simulations show that the graphene sheet can be well adsorbed on the Au(111) surface (Figure 1). The distance between graphene and the Au(111) surface was found to be (2.40 ± 0.04) Å. The 0.04 Å distance fluctuations indicates that there is only a very slight mismatch between the hexagonal cells of Au(111) and graphene. We also successfully fabricated this graphene-on-Au material and demonstrated that graphene was stably adsorbed on the gold surface (see below).

We investigated the conductivity by computing the current through the graphene-on-Au(111) material with a tip above its surface and a bias voltage of 1.0 V. We used the non-equilibrium Green function and density functional theory method (NEGF-DFT) and found that the current is on the nanoampere (nA) scale (Figure 2). For comparison, we also calculated the currents in the normal direction through the pure Au(111) and graphite surfaces under the same conditions. It is clear that the current through the graphene-on-Au(111) material is comparable to that through pure Au(111), which is much larger (by about three orders of magnitude) than the current through pure graphite.

To study the ability of the graphene-on-Au(111) composite to adsorb biomolecules with carbon-based structures, we performed MD simulations[25–28] for a segment of ssDNA (ATCGATCGATCG) on the surface of the graphene-on-Au(111) material. As shown in Figure 1, ssDNA was stably adsorbed, with all nucleobases lying nearly flat on the surface. This is due to π-stacking interactions[19] between the rings in the bases and the hexagonal cells of graphene. To characterize the degree of adsorption, we computed the distance between the atoms of the nucleobases and the surface of the graphene, as shown in Figure 3. It is clear that the distance has a very sharp peak at about 4.0 Å. This distance is quite close to the van de Waals distance between a carbon atom in graphene and carbon/oxygen/nitrogen atoms, which are the main elements in nucleobases. This shows that most of the atoms in the nucleobases are directly adsorbed by graphene, which is strong enough to destroy the helical structure of ssDNA. For comparison, we performed similar MD simulations for the same ssDNA on an Au(111) surface. The distance between the atoms of the nucleobases and the Au(111) surface is also shown in Figure 3a. It has a wide distribution from 7.0 to about 18.5 Å. In fact, the ssDNA still retains its helical structure on the Au(111) surface (see the inset of Figure 1) as the segment with six nucleobases in bulk water.[29]

We also demonstrated, experimentally, that graphene can stably adsorb on the gold surface and an ssDNA can be adsorbed on this graphene-on-gold surface. Interestingly, as

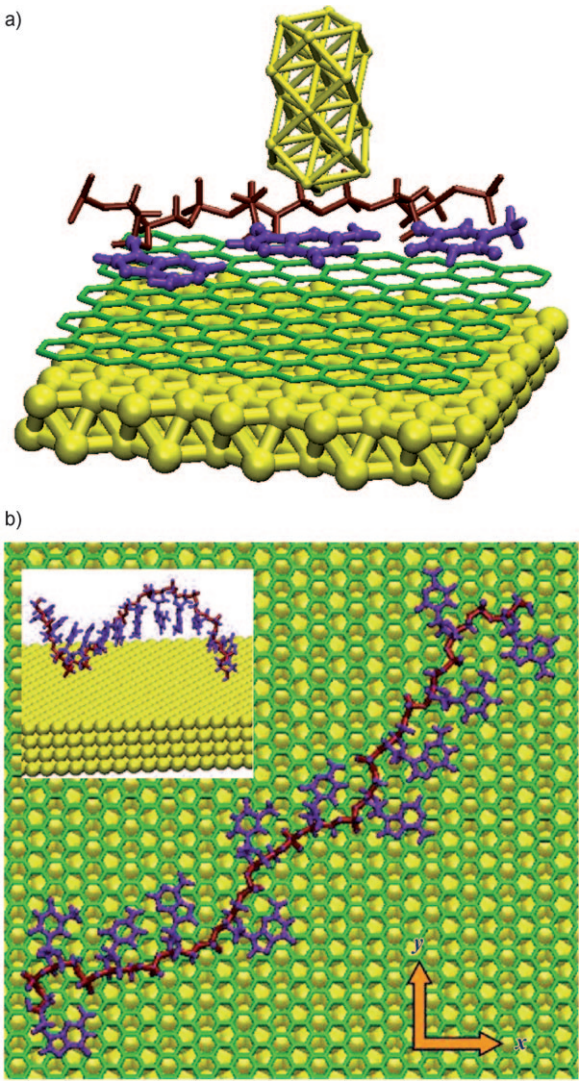

Figure 1. Schematic representation of an ssDNA nucleobase on the surface of the graphene-on-Au(111) material together with a model tip, which can be applied potentially for biosensor, biochip, STM-based DNA identification and other applications. The nucleobases and the backbone of the ssDNA are shown in violet and dark red, respectively. The graphene sheet is shown in green. The Au(111) surface is indicated by yellow spheres and sticks. a) A typical conformation of ssDNA on the graphene/Au(111) surface. The tip is represented by a rectangular solid with octahedrons inside, which is placed over the ssDNA. b) Top view of the stably adsorbed ssDNA on the surface. The inset is a typical conformation of ssDNA on Au(111).

shown in Figure 3, we found that the frequency (*F*) decreased sharply upon the flow of graphene, and reached a steady state within less then 30 seconds. Afterwards, the surface containing graphene was further exposed to a solution of DNA (20-base, 1 μM). Again, *F* decreased rapidly to a steady state within 10 seconds. The decease of *F* confirms the adsorption of graphene at the gold surface or DNA at the graphene surface. Interestingly, the kinetics for both processes is extremely fast, within seconds. Noteworthy, previous studies suggested that thiolated DNA adsorbed at gold surfaces with much slower kinetics (several hours).[30] This sharp difference suggests that

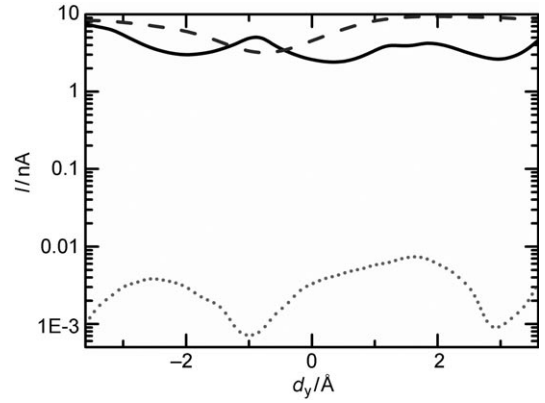

Figure 2. Currents through graphene-on-Au(111) (——), pure Au(111) (-----), and pure graphite (•••••) in the normal direction with respect to the moving distance of the tip in the *y* direction, d_y.

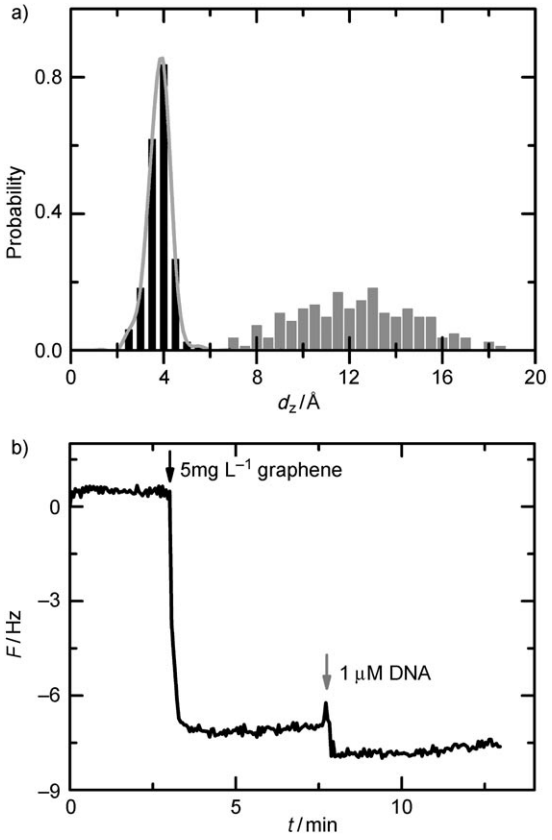

Figure 3. a) Probability of finding the atoms in the nucleobases of ssDNA at a distance d_z from the graphene-on-Au(111) surface (black columns) and the Au(111) surface (grey columns), respectively. The curve is the spline-fitting for the case of our material. b) Experimental frequency, monitored in the real-time mode. First, a solution of graphene (5 mg mL^{-1}) was added and then a solution of DNA (1 μM) was passed through the system.

both graphene-on-gold and graphene–DNA adsorptions are fairly strong and stable.

Next, we demonstrate that both the current and the signal-to-noise ratio can be increased considerably by using this graphene-on-Au(111) material as a substrate when the tip moves over the nucleobases, by means of NEGF-DFT computations[31–35] with the gDFTB package.[36,37] As shown in Figure 4, for all three adenine bases, there are two maxima, spaced by about 2.0 Å. We note that although there are differences between the three current signals, the positions of the maxima are quite consistent. Vertical displacements of the three curves may be due to different positions of the adenine bases with respect to the graphene lattice. This phenomenon was seen for the other nucleobases as well. For the thymine bases, a distinct peak appeared with two maxima spaced by about 1.5 Å. The distance between this peak and its nearest-neighbor maximum is about 2.2 Å. This peak results from the CH_3 fragment in thymine, which is similar in shape to a tetrahedron. This fragment dramatically increases the coupling between the tip and thymine by reducing the distance between them. There are three maxima in the current signals for the guanine bases. The distances between the neighboring maxima are about 2.6 and 1.8 Å, respectively. Two maxima appear for the cytosine bases that are spaced by about 1.4 Å. In Table 1, we summarize the distinguishing properties of the current signals for the different nucleobases. It is clear that although there is some variability in the currents among different scans of the same base, there are enough distinguishing properties to identify the base type.

As a result, the current signals calculated here show clearly distinguishable characteristics for different nucleobases. These observations are in direct contrast to the results obtained for conventional Au(111) surfaces, which lead to ambiguous signals and do not allow us to distinguish between the bases in ssDNA. This is due to the fact that the noise of the electric current through the nucleobases is so strong that it is usually comparable to the signals.[38] It is apparent that these signals can be used to identify individual nucleobases with the help of the tip, which is expectable to be applied for single-molecule DNA sequencing via atomic force microscopy (AFM) or STM.

Finally, we note that the experiments by Varghese et al.[18] and Lu et al.[20] implied that the DNA may stably adsorbed on graphene (or graphene oxide), and charges can be transferred through the DNA sequence to graphene. Herein, we show—through theoretical computations—that the adsorption of biomolecules on our graphene-on-Au(111) composite is very stable, and the conductivity of this material is excellent, even along the vertical direction, which results in a very high signal-to-noise ratio of the resonant currents through the different nucleobases. We note that we have used gold because gold has an excellent electric conduction—better than that of other metals—which has been widely used in the laboratory.

3. Conclusions

We have shown that a material containing a sheet of graphene on a Au(111) surface has both a good conductivity and the ability to stably adsorb biomolecules with carbon-based ring structures. One application of this material is to serve as substrate for various devices and sensors in order to effectively reduce noise and greatly enhance the signal-to-noise ratios. We have shown an example for ssDNA adsorption on this graphene-on-Au(111) surface. Remarkably, the signal-to-noise ratio

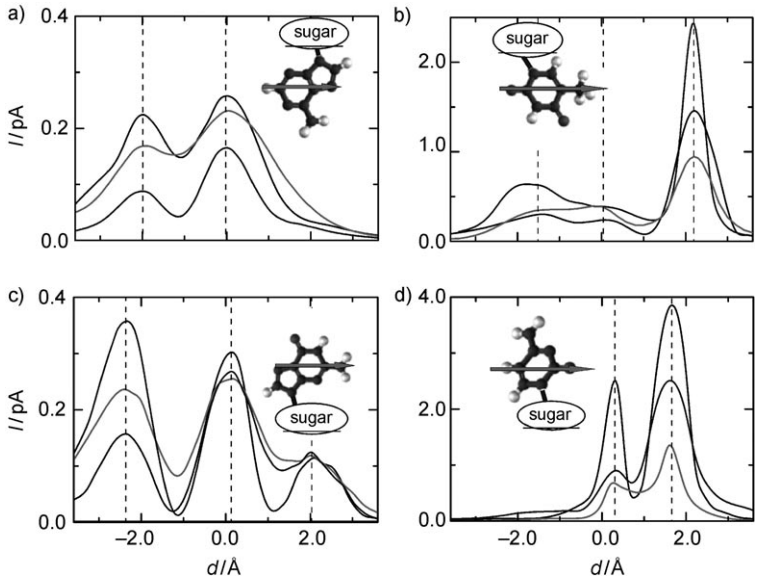

Figure 4. Current, *I*, for one-dimensional moving over all the nucleobases in ssDNA. The arrows in the insets represent the moving paths. The ovals in the insets denote the sugar rings of each nucleobase. The moving distance, *d*, is referenced from the middle of the hexagonal ring in each base: a) adenine, b) thymine, c) guanine, d) cytosine.

Table 1. Distinguishing features of the current signals for different nucleobases by one-dimensional moving along the paths shown in the insets of Figure 4

Nucleobase	Characteristics of the current signals	
	Number of maxima	Distance between neighboring maxima
Adenine	Two	2.0 Å
Thymine	Two with one distinct peak on the right	1.5 and 2.2 Å
Guanine	Three	2.6 and 1.8 Å
Cytosine	Two	1.4 Å

is so high that the resonant currents through the different nucleobases are clearly distinguishable. This provides an alternative method for high-accuracy DNA identification. Moreover, considering that at present it is still very difficult to sequence long strands of DNA and DNA with repeating segments, the example of the ssDNA segment presented here, using graphene-on-Au(111) as the substrate and with the tip being moved over it, shows that this kind of quantum-current-based DNA identification is feasible. It may provide a novel strategy for DNA sequencing, particularly for DNA strands with repeating segments. Therefore, we expect that our findings will greatly enhance the applications of the electric-conduction properties of single biomolecules in nanobiology and biotechnology, including high-accuracy biodevices and biosensors as well as DNA sequencing.

Experimental Section

Quartz crystal microbalance experiments were performed using a newly developed QCM-D instrument (Q-Sense Inc.), which provides reliable frequency (*F*) measurement in a flow cell with precise temperature control.[39] *F* indicates that mass changes occur at the crystal surfaces. In our experiments, quartz crystals coated with a gold film were employed, which were extensively cleaned following the reported protocol.[39,40] Then, chips were blow-dried under nitrogen and placed into the measurement chamber. First, distilled water was passed through the chamber to reach a steady state, followed by a solution of graphene (5 mg mL^{-1}). After graphene adsorption, a 1 μM DNA solution (20 base, 5′-AAC ACT GAT CGC TAC TAC AT-3′) was further passed through the chamber. The frequency changes were simultaneously monitored for all these processes in the real-time mode. More details on the experimental methods can be found in the Supporting Information.

Acknowledgements

We acknowledge Profs. Jun Hu and David Tománek for helpful discussions. This work was supported by NNSFC (10674146 and 10825520), NBRPC (2007CB936000 and 2010CB934504), the Ministry of Health (2009ZX10004-301), the Knowledge Innovation Program of the Chinese Academy of Sciences, and the Shanghai Supercomputer Center of China.

Keywords: biosensors · conducting materials · molecular devices · nanocomposites · nanomaterials

[1] J. Shendure, H. Ji, *Nat. Biotechnol.* **2008**, *26*, 1135 – 1145.
[2] M. Zwolak, M. Di Ventra, *Rev. Mod. Phys.* **2008**, *80*, 141 – 165.
[3] A. Nitzan, M. A. Ratner, *Science* **2003**, *300*, 1384 – 1389.
[4] J. J. Kasianowicz, E. Brandin, D. Branton, D. W. Deamer, *Proc. Natl. Acad. Sci. USA* **1996**, *93*, 13770 – 13773.
[5] B. Song, M. Elstner, G. Cuniberti, *Nano Lett.* **2008**, *8*, 3217 – 3220.
[6] H. An, J. Huang, M. Lü, X. Li, J. Lü, H. Li, Y. Zhang, M. Li, J. Hu, *Nanotechnology* **2007**, *18*, 225101 – 225105.
[7] A. Bensimon, A. Simon, A. Chiffaudel, V. Croquette, F Heslot, D. Bensimon, *Science* **1994**, *265*, 2096 – 2098.
[8] S. Roy, H. Vedala, A. D. Roy, D. Kim, M. Doud, K. Mathee, H. Shin, N. Shimamoto, V. Prasad, W. B. Choi, *Nano Lett.* **2008**, *8*, 26 – 30.
[9] X. Guo, A. A. Gorodetsky, J. Hone, J. K. Barton, C. Nuckolls, *Nat. Nanotechnol.* **2008**, *3*, 163 – 167.
[10] E. Shapir, H. Cohen, A. Cohen, C. Cavazzoni, D. A. Ryndyk, G. Cuniberti, A. Kotlyar, R. Difelice, D. Porath, *Nat. Mater.* **2008**, *7*, 68 – 74.
[11] M. Zhou, Y. Zhai, S. Dong, *Anal. Chem.* **2009**, *81*, 5603 – 5613.
[12] J. C. Meyer, A. K. Geim, M. I. Katsnelson, K. S. Novoselov, T. J. Booth, S. Roth, *Nature* **2007**, *446*, 60 – 63.
[13] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, A. A. Firsov, *Science* **2004**, *306*, 666 – 669.
[14] X. Wang, Y. Ouyang, X. Li, H. Wang, J. Guo, H. Dai, *Phys. Rev. Lett.* **2008**, *100*, 206803 – 206806.
[15] Y.-W. Son, M. L Cohen, S. G. Louie, *Nature* **2006**, *444*, 347 – 349.
[16] K. Chang, S. Berber, D. Tománek, *Phys. Rev. Lett.* **2008**, *100*, 236102 – 236105.
[17] P. Avouris, Z. Chen, V. Perebeinos, *Nat. Nanotechnol.* **2007**, *2*, 605 – 615.
[18] N. Varghese, U. Mogera, A. Govindaraj, A. Das, P. K. Maiti, A. K. Sood, C. N. R. Rao, *ChemPhysChem* **2009**, *10*, 206 – 210.
[19] G. B. McGaughey, M. Gagne, A. K. Rappe, *J. Biol. Chem.* **1998**, *273*, 15458 – 15463.

[20] C.-H. Lu, H.-H. Yang, C.-L. Zhu, X. Chen, G.-N. Chen, *Angew. Chem. Int. Ed.* **2009**, *48*, 4785 – 4787.
[21] X. Wang, Y. Ouyang, X. Li, H. Wang, J. Guo, H. Dai, *Phys. Rev. Lett.* **2008**, *100*, 206803 – 206806.
[22] K. S. Kim, Y. Zhao, H. Jang, S. Y. Lee, J. M. Kim, K. S. Kim, J.-H. Ahn, P. Kim, J.-Y. Choi, B. H. Hong, *Nature* **2009**, *457*, 706 – 710.
[23] L. Song, L. Ci, W. Gao, P. M. Ajayan, *ACS Nano* **2009**, *3*, 1353 – 1356.
[24] J.-P. Jalkanen, M. Halonen, D. Fernández-Torre, K. Laasonen, L. Halonen, *J. Phys. Chem. A* **2007**, *111*, 12317 – 12326.
[25] R. H. Zhou, X. H. Huang, C. J. Margulis, B. J. Berne, *Science* **2004**, *305*, 1605 – 1609.
[26] X. J. Gong, J. Y. Li, H. J. Lu, R. Z. Wan, J. C. Li, J. Hu, H. P. Fang, *Nat. Nanotechnol.* **2007**, *2*, 709 – 712.
[27] E. Lindahl, B. Hess, D. van der Spoel, *J. Mol. Model.* **2001**, *7*, 306 – 317.
[28] T. A. Darden, D. York, *J. Chem. Phys.* **1993**, *98*, 10089 – 10092.
[29] J. Isaksson, S. Acharya, J. Barman, P. Cheruku, J. Chattopadhyaya, *Biochemistry* **2004**, *43*, 15996 – 16010.
[30] R. Georgiadis, K. P. Peterlinz, A. W. Peterson, *J. Am. Chem. Soc.* **2000**, *122*, 3166 – 3173.
[31] B. Song, D. A. Ryndyk, G. Cuniberti, *Phys. Rev. B* **2007**, *76*, 045408 – 045414.
[32] A.-P. Jauho, N. S. Wingreen, Y. Meir, *Phys. Rev. B* **1994**, *50*, 5528 – 5544.
[33] J. Taylor, H. Guo, J. Wang, *Phys. Rev. B* **2001**, *63*, 121104(R) – 121107(R).
[34] M. Brandbyge, J.-L. Mozos, P. Ordejon, J. Taylor, K. Stokbro, *Phys. Rev. B* **2002**, *65*, 165401 – 165417.
[35] A. R. Rocha, V. M. Garcia-Suarez, S. Bailey, C. Lambert, J. Ferrer, S. Sanvito, *Phys. Rev. B* **2006**, *73*, 085414 – 085435.
[36] A. Di Carlo, M. Gheorghe, P. Lugli, M. Stenberg, G. Seifert, T. Frauenheim, *Phys. B* **2002**, *314*, 86 – 90.
[37] M. Elstner, D. Porezag, G. Jungnickel, J. Elsner, M. Haugk, T. Frauenheim, S. Suhai, G. Seifert, *Phys. Rev. B* **1998**, *58*, 7260 – 7268.
[38] H. Wang, Z. Tang, Z. Li, E. Wang, *Surf. Sci.* **2001**, *480*, L389 – L394.
[39] F. Hook, M. Rodahl, B. Kasemo, P. Brzezinski, *Proc. Natl. Acad. Sci. USA* **1998**, *95*, 12271 – 12276.
[40] R. Lao, S. Song, H. Wu, L. Wang, Z. Zhang, L. He, C. Fan, *Anal. Chem.* **2005**, *77*, 6475 – 6480.

Received: September 20, 2009
Published online on January 7, 2010

