Electron transport through single conjugated organic molecules: Basis set effects in ab initio calculations

San-Huang Ke
Department of Chemistry, Duke University, Durham, North Carolina 27708-0354, USA

Harold U. Baranger
Department of Physics, Duke University, Durham, North Carolina 27708-0305, USA

Weitao Yang
Department of Chemistry, Duke University, Durham, North Carolina 27708-0354, USA

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We investigate electron transport through single conjugated molecules—including benzenedithiol, oligophenylene ethynlenes of different lengths, and a ferrocene-containing molecule sandwiched between two gold electrodes with different contact structures—by using a single-particle Green function method combined with density functional theory calculation. We focus on the effect of the basis set in the ab initio calculation. It is shown that the position of the Fermi energy in the transport gap is sensitive to the molecule-lead charge transfer which is affected by the size of basis set. This can dramatically change, by orders of magnitude, the conductance for long molecules, though the effect is only minor for short ones. A resonance around the Fermi energy tends to pin the position of the Fermi energy and suppress this effect. The result is discussed in comparison with experimental data. © 2007 American Institute of Physics. [DOI: 10.1063/1.2770718]

I. INTRODUCTION

Electron transport through single conjugated organic molecules has attracted considerable experimental attention1–12 because of the convenience of the chemical assembly and their delocalized electronic states and the resulting small highest occupied molecular orbital (HOMO)-lowest unoccupied molecular orbital (LUMO) gap which is very useful in molecular electronics especially for the operation under low bias voltages. Theoretically, to understand the transport properties of junctions bridged by these molecules and to be able to calculate their conductance are important in view of both applications and fundamental physics. Regarding the comparison between theory and experiment, however, large discrepancies have been found for some conjugated molecules between theoretical predictions13–17 and experimental conductances.1–6 Many efforts have been made on the theoretical side18–23 to understand this discrepancy and several possible reasons have been discussed, for example, the self-interaction error and the underestimation of the transport gap in density functional theory (DFT) based ab initio calculations.21,24 and the neglect of the dynamical correlation effect in the noninteracting Landauer formalism.20,22

In this paper, we investigate a fundamental technical issue in all ab initio transport calculations: the effect of the basis set. We find that this effect can also cause a significant change, up to orders of magnitude, in the resulting conductance, depending on the molecular feature and the molecule-lead coupling strength. It is shown that for conjugated organic molecules with a small HOMO-LUMO gap the position of the Fermi energy ($E_F$) of the leads in the transport gap, which is determined by the molecule-lead charge transfer, is sensitive to the size of basis set. For long molecules different positions of $E_F$ can lead to significant change in the conductance, though for short molecules and strong coupling the effect may be only minor. We further show, by considering different molecule-lead contact structures, that a resonance around the Fermi energy tends to pin the position of $E_F$ and thus suppress the basis set effect, indicating that this effect will be much less important for the strong coupling limit which gives a large equilibrium conductance.

II. COMPUTATION

The conjugated molecules considered in our calculation include a short benzenedithiol (BDT) molecule, oligophenylene ethynlenes (OPE) of different lengths, and a ferrocene-containing (FC) molecule, sandwiched between two gold electrodes, as shown in Figs. 1 and 6. We only consider the energy favorable coplanar structure for the OPE and FC molecules without any torsional fluctuations between the phenyl rings, which has been investigated previously for an OPE3 molecule.17 Two models for the lead are adopted, a thin Au(001) wire as shown in Fig. 1 and a 5 × 5 Au(111) surface as shown in Fig. 3; both models are possible to occur in experiments.7,25–34 We also consider two different molecule-lead contacts, through a flat Au surface or through an apex Au atom, both of which are also possible to occur in experiments.7,25–28,33,34

We adopt a single-particle Green function method35,36 combining a Landauer formula with ab initio DFT37 electronic structure calculation to investigate the electron transport through the junctions.35,36,38 In practice, we divide an infinitely long Au-molecule-Au system into three parts: left
lead, right lead, and device region which contains the molecule and large parts of the Au leads (see, for instance, Fig. 1) for accommodating fully the molecule-electrode interaction. The self-consistent Kohn-Sham Hamiltonian of the device region and the self-energies from the two semi-infinite Au leads (the two subsystems are treated on the same footing) are used to construct a single-particle Green function from which the transmission coefficient at any energy is calculated. The conductance, $G$, then follows from a Landauer-type relation. The detailed computational techniques have been described previously.36 For the DFT electronic structure calculation, we make use of the optimized Troullier-Martins pseudopotentials39 for the atomic cores. The PBE version of the generalized gradient approximation40 (GGA) is used for the electron exchange and correlation. [Test calculations show a minor difference between GGA and local density approximation (LDA) for transport]. The wave functions are expanded using a numerical basis set41 of different sizes: single zeta plus polarization (SZP), double zeta plus polarization (DZP), and triple-zeta plus double polarization (TZDP), and triple-zeta plus triple polarization (TZTP). The atomic structure of the junctions, including the molecular structure and the first two layers of the lead surface, and the molecule-Au separation, are fully optimized by minimizing the atomic forces on the atoms to be smaller than 0.02 eV/Å using the DZP basis set. Possible differences from this optimized configuration in experiments are not considered.

III. RESULTS AND DISCUSSION

To avoid a computational cost which is too large for the large size of basis set, we first consider the thin $\sqrt{2} \times \sqrt{2}$ Au(001) nanowire model for the lead, as shown in Fig. 1. Eight atomic layers of the lead surface are included in the extended molecule to ensure good convergence for the molecule-lead interaction. The transmission function and the equilibrium conductance for the two junctions bridged by the OPE5 and FC molecules are given in Figs. 2(a) and 2(b), respectively.42 As can be seen, for both systems varying the size of the basis set changes the position of $E_F$ of the lead in the molecular HOMO-LUMO gap. This position is determined by the molecule-lead charge transfer; for long-chain molecules the charge transfer will be around the contact region and form a contact dipole. Different sizes of basis set will affect the amount of this molecule-lead charge transfer, until it reaches a converged value. For usual ground-state energy a small change in the charge transfer will have only a minor effect. However, for molecular conductance, this can have a significant effect because it depends critically on the position of $E_F$ in the transport gap, which is very sensitive to the charge transferred—the charge in the tail of the broadened HOMO or LUMO state.

For the OPE5 junction, the SZP basis set leads to $E_F$ entering into the LUMO state and, therefore, a very large equilibrium conductance. The DZP basis set begins to put $E_F$ near the tail of the LUMO state and reduces the conductance by about a factor of 40. When we further go to the TZDP and TZTP basis sets, $E_F$ goes further away from the LUMO state and the conductance decreases further. The almost identical results for the TZDP and TZTP basis sets indicate that they have reached the converged limit. Qualitatively, the DZP basis set already gives a good result though it is not good enough quantitatively.

The result for the FC molecule (Fig. 2(b)) shows the same trend: The SZP basis set leads to $E_F$ entering into the broadened LUMO state and a large conductance while the

![FIG. 1. (Color online) Structures of two molecular junctions: (a) Au(001)-OPE5-Au(001) and (b) Au(001)-FC-Au(001). Only the extended molecule (device region) is shown, which contains eight atomic layers of the lead surfaces. The lead is a thin $\sqrt{2} \times \sqrt{2}$ Au(001) wire.](image)

![FIG. 2. (Color online) Transmission functions of the two molecular junctions shown in Fig. 1: (a) Au(001)-OPE5-Au(001) and (b) Au(001)-FC-Au(001). Different basis sets and the resulting equilibrium conductance (in units of $G_0 = 2e^2/h$) are indicated in the legend.](image)
DZP and TZDP basis sets put $E_F$ in the middle of the gap and a much smaller conductance. From SZP to TZDP (TZTP) the relative change in conductance is more than two orders of magnitude—an effect which has not been found for any other property.

Next we investigate the basis set effect for conjugated molecular bridges with different lengths and also for a more realistic Au(111)-surface electrode. We consider two large $5 \times 5$ Au(111) periodic surfaces as the leads bridged by the following molecules of different lengths: BDT, OPE3, OPE5, and the FC molecule. To reduce the computational cost here we consider only the SZP and DZP basis sets and include only four atomic layers of the Au(111) surface in the extended molecule, as shown in Fig. 3. To check the convergence with the basis set we also carry out a DZDP calculation for the OPE3 system.

From the calculated transmission functions shown in Fig. 4 one can see the same effect as we discussed previously: the two different sizes of basis set affect the molecule-lead charge transfer and cause a shift of about 0.5 eV for the position of $E_F$ in the HOMO-LUMO gap. The use of the larger DZDP basis set in the test calculation for the OPE3 system leads to only a further $\sim 0.1$ eV shift [see Fig. 4(b)] and the change in the equilibrium conductance is minor, indicating that the DZP results are almost converged. For the BDT, OPE3, and OPE5 series, the equilibrium conductance decreases along with the increasing molecule length. For the longest one, OPE5, the basis set effect causes about one order of magnitude difference in the conductance while for the shorter one, OPE3, the difference is only a factor of 2, and for the shortest one, BDT, it becomes minor. This behavior is a result of the observation that along with the increase of the molecule length the smaller SZP basis set tends to put $E_F$ closer and closer to the LUMO state while the larger DZP basis set tends to put it closer and closer to the middle of the gap. As a result, the difference between the two basis sets grows as the molecule gets longer.

Note that one can see an approximate exponential decay of the conductance as the molecule gets longer: from BDT to OPE3, and from OPE3 to OPE5, the conductance decreases approximately by a factor of 20 [see the legend of Figs. 4(a)–4(c)], given by the almost-converged DZP calculation. This is a natural behavior of coherent tunneling and the decay ratio, $\beta$, is a property of the molecule. In order to show more clearly this decay with the length of molecule we plot it in Fig. 5 with the corresponding $\beta$ values listed in the legend. Here we can also see a significant basis-set effect on the decay and the resulting $\beta$ value: For the almost-converged DZP basis set the decay is rapid exponentially while for the smaller SZP basis set the decay is much slower and is not quite exponential, as is shown in Fig. 5. The $\beta$ value from the DZP calculation is about 0.21 Å⁻¹ which is very close to an available experimental datum, 0.22 Å⁻¹, for a conjugated molecule, carotenoid polyenes. The agreement between theory and experiment for the exponential decay in the case studied here is similar to that found in other cases. For instance, experimental values and theoretical values of $\beta$ for another conjugated molecule, oligophenylene, are found to be $0.35 - 0.5$ Å⁻¹. Also, for alkane and peptide chains, $\beta$ is in
the range of 0.7–0.9 Å⁻¹ experimentally and theoretically. Naturally, the conductance of conjugated oligomers decays more slowly with chain length than that of saturated molecules; thus, the values of β for conjugated chains are considerably smaller than those for saturated chains.

In the case of the FC molecule the situation is different, where the SZP basis set puts the EF slightly closer to the LUMO while the DZP puts it slightly closer to the HOMO, and as a result of this symmetry, the two resulting conductances become quite close. Thus in general, the strong system dependence of the basis set effect indicates that it can cause unpredictable numerical errors which are specific to the system investigated. However, this effect can be expected to be small for short molecules and strong coupling, such as for the Au-BDT-Au system, where the strong coupling allows lead states tunneling into the molecule to meet in the middle (sometimes called metal-induced gap states), and as a result, the transmission coefficient is fairly large and flat in the gap, as is shown in Fig. 4(a).

In the following we consider a possible experimental situation in which the molecule-gold connection is through an apex gold atom, as suggested by a scanning tunneling microscope (STM) experiment. We consider two possibilities: (1) the connection is straight with an optimized Au–S bond length, as shown in Fig. 6(a) for a BDT molecule, which is possible to occur when the STM tip is pulled from the gold surface, as suggested in Refs. 7, 25, and 26; (2) the connection and the molecule-lead separation are optimized, as shown in Figs. 6(d)–6(g). The structure optimization calculation for Au(111)-Au-BDT-Au-Au(111) junction shows three metastable structures, as shown in Figs. 6(b)–6(d), which lower the total energy with respect to the straight connection in Fig. 6(a). The most stable structure is given in Fig. 6(d). We further find that for the longer molecules, OPE3, OPE5, and FC, the most stable optimized contact structure is similar to that in Fig. 6(d). Therefore, we only give these optimized structures while omitting those with a straight connection in Fig. 6 for the longer molecules.

The transmission functions for the four junctions are given in Fig. 7. There are several features to notice in the result. First, the presence of the apex gold atom at the contacts changes totally the transport property of the junctions.

The very narrow peaks indicates that the molecule-lead coupling is significantly weakened as compared to the case without the apex gold atom. This will significantly reduce the current for large bias voltages. Second, the relaxation of the contact structure has only a small effect once the connection is through an apex gold atom. Third, a sharp resonance peak occurs around the Fermi energy except for the FC molecule where the peak near EF is very small [see Fig. 7(d)].

The electronic state corresponding to this new resonance peak is originated from the Au–S–C complex at the contacts rather than from any “pure” molecular orbital of the isolated benzene or OPE molecule. This resonance peak was found previously also by other calculations for straight-connected BDT systems. In fact, for the short BDT bridge, even for the connection without the apex gold atom the HOMO and LUMO states shown in the transmission function [see Fig. 4(a)] are not those of the insolated benzene molecule but are created by the strong molecule-lead interaction through the Au–S–C complex. This is evident by comparing the HOMO-LUMO gap of an isolated benzene molecule, ~5.1 eV, and that shown in the transmission function, ~3.5 eV. Indeed, for the strong molecule-lead interaction the “molecule” in the junction is not well defined anymore. Since the interaction around the contacts affects significantly the electronic states around the Fermi energy, a structural change of the contact (with and without the apex gold atom) can have a drastic effect on T(E), as is shown by the present calculation.
check if it is an artifact due to the issues in DFT we perform a 6-31G* basis set for H, C, and S atoms and a Crenbs basis issue of xc discontinuity. The calculation is carried out using theory which is self-interaction free and does not have the continuity in the exchange-correlation DFT, such as self-interaction error or the absence of the dis-

the new resonance peak has anything to do with issues in apex gold atom, it is unclear whether or not the occurrence of general behavior for conjugated molecules connected by an 

Although the present calculation shows that it is a quite general behavior for conjugated molecules connected by an apex gold atom, it is unclear whether or not the occurrence of this new resonance peak has anything to do with issues in DFT, such as self-interaction error or the absence of the discontinuity in the exchange-correlation (xc) potential. 

to check if it is an artifact due to the issues in DFT we perform a test transport calculation for a Au(001)-Au-BDT-Au-Au(001) junction (see the inset of Fig. 8) using Hartree-Fock theory which is self-interaction free and does not have the issue of xc discontinuity. The calculation is carried out using a 6-31G* basis set for H, C, and S atoms and a Crenbs basis set for Au atom, and the result is given in Fig. 8. As can be seen, the resonance peak around the Fermi energy remains, indicating that it is a general behavior instead of an artifact.

Finally, the basis set effect is significantly reduced compared to the previous cases without the apex gold atom. The small effect of the basis set can be understood by considering the entering of the Fermi energy into the new resonance state. Because of it, a small change in the molecule-lead charge transfer cannot shift the position of the Fermi energy a large amount due to the total charge conserving. This behavior indicates that the effect of the basis set will be much less important in the strong coupling limit which gives a large equilibrium conductance.

IV. COMPARISON TO EXPERIMENTAL RESULTS

Finally, we would like to make some comparison between the present results and experimental data. The present result of equilibrium conductance for the Au(111)-BDT-Au(111) junction (~0.1G0) is too large compared to experimental reports. Similar results were also obtained by other DFT-Green function (GF) calculations. This overestimation is still an open problem and can be due to several possibilities: the difference in the atomic structure of the junction between the real experimental situation and the calculation; the self-interaction error; and the underestimation of the transport gap in the DFT electronic structure calculation. Because of the latter issue the conductance of the OPE3 molecule (~0.006G0) and the OPE5 molecule (~0.0003G0) are also expected to be overestimated.

On the other hand, in real experiments, when a molecule is long enough incoherent or inelastic effects may play a role or even take over, and, as a result, the conductance will decay more slowly or even linearly with increasing molecule length. In such case the theoretical calculation for coherent tunneling may underestimate the conductance. In a certain range of molecule length these two errors may cancel with each other.

For OPE3 molecule the present result of conductance is still too large compared to some experimental reports while the very small conductance for OPE5 is in agreement with the experimental observation in Ref. 11. However, our result of a very small conductance (~0.00002G0) for the FC molecule differs qualitatively from the experimental result which shows a good conduction. So far it is not clear how to understand this discrepancy. One possible reason is the structure difference between the experiment and calculation. For example, in the experiment the molecule-lead connection might be through an apex gold atom which will significantly increase the current for small bias voltages, as shown by our calculation [see Fig. 7(d)]. Additionally, the scissor mode
made by the ferrocene moiety (i.e., rotation of the two five-member rings with respect to each other) might also allow a higher conductance state to be realized, although this might not account for the big qualitative discrepancy. Another possibility is the chemical absorption on the lead surface in the experiment which was partially done in solution first. The chemical absorption may change the work function of the surface of the electrode or form a dipole layer on the surface, both of which can change the lineup between the Fermi energy and the HOMO or LUMO state and therefore cause a large increase in the conductance.

V. SUMMARY

We have investigated electron transport through different single conjugated molecules of different length by using single-particle Green function method combined with density functional theory calculation. It is shown that the convergence with respect to the size of basis set is important for ab initio transport calculations since the position of the Fermi energy in the transport gap is sensitive to the molecule-lead charge transfer which is affected by different sizes of basis set. It is shown that this basis set effect can be dramatic, up to orders of magnitude, while it is only minor for short molecules and strong coupling.

Our calculation also shows that a resonance around the Fermi energy tends to pin the position of the Fermi energy and suppress this effect, indicating that it will be much less important for the strong coupling limit which gives a large equilibrium conductance. Comparing to experiments, our result for the OPE molecules is in agreement with some experimental reports. The result for the FC molecule is not in qualitative agreement and the reason needs further experimental and theoretical work to clarify.

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35 In a previous work (Ref. 11) we calculated the OPE5 and FC systems with thicker Au(001) leads adopting the SZP basis set. The results are qualitatively consistent with the present calculation using the thinner Au(001) lead and adopting the SZP basis set.
45 In a previous calculation (Ref. 11) we obtained a large equilibrium conductance for both the OPE5 and FC systems due to the use of a too small basis set (SZP).