

Raman Scattering in Molecular Junctions: A Pseudoparticle Formulation

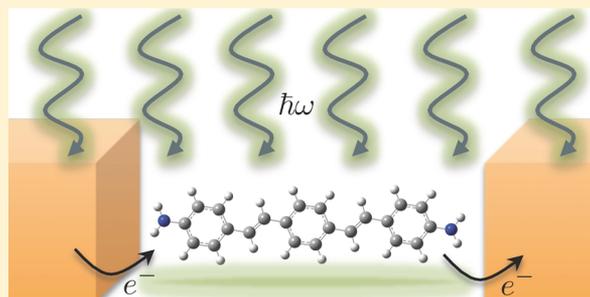
Alexander J. White,[†] Sergei Tretiak,[‡] and Michael Galperin^{*,†}

[†]Department of Chemistry and Biochemistry, University of California San Diego, La Jolla, California 92093, United States

[‡]Theoretical Division, Center for Nonlinear Studies (CNLS), and Center for Integrated Nanotechnologies (CINT), Los Alamos National Laboratory, Los Alamos, New Mexico 87545, United States

Supporting Information

ABSTRACT: We present a formulation of Raman spectroscopy in molecular junctions based on a many-body state representation of the molecule. The approach goes beyond the previous effective single orbital formalism and provides a convenient way to incorporate computational methods and tools proven for equilibrium molecular spectroscopy into the realm of current carrying junctions. The presented framework is illustrated by first principle simulations of Raman response in a three-ring oligophenylene vinylene terminating in amine functional groups (OPV3) junction. The calculated shift in Stokes lines and estimate of vibrational heating by electric current agree with available experimental data. In particular, our results suggest that participation of the OPV3 cation in Raman scattering under bias may be responsible for the observed shift, and that the direction of the shift depends on renormalization of normal modes. This work is a step toward atomistic quantum ab initio modeling of the optical response of nonequilibrium electronic dynamics in molecular junctions.



KEYWORDS: Raman scattering, molecular junctions, pseudoparticle nonequilibrium Green functions, time-dependent density functional theory (TDDFT), oligophenylene-vinylene (OPV), vibrational heating

Molecular electronics promises to harness electronic functionality over an area of no more than a few molecules thus approaching the fundamental size limit of molecular electronic devices.¹ Our progress in this field is subject to the availability of advanced fabrication technologies and experimental capabilities to precisely characterize the structure and monitor the underlying fundamental electronic dynamics. The first observation of Raman spectroscopy enhancement for molecules chemisorbed on metal surfaces (SERS)^{2,3} has manifested an important optical tool for single molecule detection.^{4,5} Since then the field has progressed rapidly.^{6–9} SERS is known to be dominated by *hot spots* (areas of particularly strong electromagnetic field enhancement).¹⁰ The ability to produce nanometer scale gaps in metal junctions^{11–13} paved the way for the application of SERS in molecular electronics as diagnostic and control tool.^{14–16} In particular, Raman spectroscopy was used to estimate bias induced vibrational and electronic heating in molecular junctions^{17–19} to reveal the structure of single-molecule junctions^{20–23} and to estimate orientation of a molecule in junction.^{24,25} Correlations between the Raman signal and conductance due to junction dynamics suggest the possibility to characterize electronic dynamics by optical means.^{18,26,27}

Experimental advances have driven theoretical interest in this field. Several theoretical approaches have been put forward to analyze and explain existing data as well as to propose future experiments.^{15,28} In particular, in our previous publications we

combined a nonequilibrium Green's function description of quantum transport with a generalized scattering theory of the Raman flux, thus providing the first theoretical description of Raman scattering in such systems. Within simple models, we applied the theory to study bias induced vibrational^{29,30} and electronic^{31,32} heating, charge transfer contribution to SERS³³ and time-dependent correlations between conductance and Stokes signal.^{1,26,34–36}

To this point, existing studies of Raman scattering under nonequilibrium electronic conditions have utilized a non-interacting orbital-based approach (a single-electron mean-field picture), which becomes inadequate in the presence of strong interactions (e.g., molecule-plasmon coupling) in the system.³⁷ On the other hand, only ab initio simulations based on equilibrium theory of Raman scattering were reported in the literature for molecules adsorbed on metal surfaces^{21,38–44} and in junctions.^{45–47} This necessitates the need for theoretical techniques enabling modeling of optical response of nonequilibrium electronic system in molecular junctions using advanced quantum-chemical methods able to describe the underlying many-body physics.

Here we present a pseudoparticle nonequilibrium Green function (PP-NEGF) formulation for Raman scattering probes

Received: October 22, 2013

Revised: December 12, 2013

Published: January 21, 2014

in current carrying molecular junctions and apply it to first principle simulations of Raman scattering in an OPV3 junction (see Figure 1). This molecular system has been used in Raman

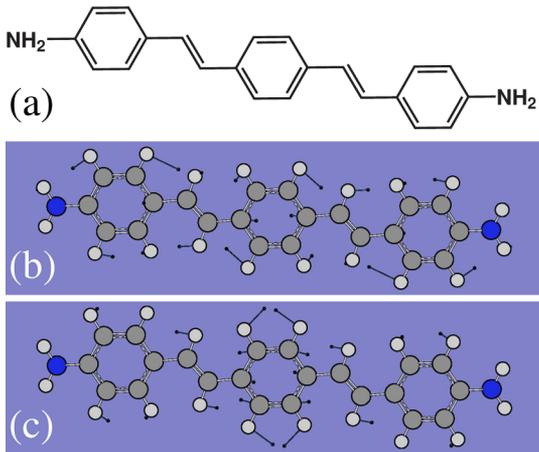


Figure 1. A three-ring oligophenylene vinylene terminating in amine functional groups (OPV3) molecule. Shown are (a) molecular structure and normal modes of neutral OPV3 at frequencies (b) 1199 cm^{-1} and (c) 1608 cm^{-1} . Created by GaussView 5.

spectroscopy experiments.¹⁹ The study is the first attempt of ab initio simulation within a nonequilibrium theory of Raman scattering. Our eventual goal is a realistic description of optical response in junctions, where the PP-NEGF molecular Raman scattering (presented here) should be accompanied by PP-NEGF description of interactions with plasmon excitations in the contacts (as presented in ref 37).

We stress that the PP-NEGF approach (relying on the many-body states) introduced here is fundamentally different from the quasiparticle considerations (operating with single-particle orbitals) described in our previous publications.^{26,29–36} Particularly, due to the many-body states representation, the PP-NEGF formulation allows one to account for all intramolecular interactions exactly. It also provides a possibility of a convenient map to the language of vibronic (dressed) states. Note that while the standard (Redfield) quantum master equation in principle can also account exactly for the intramolecular interactions, it is applicable only to the unphysically high-temperature regime ($k_B T \gg \Gamma$)⁴⁸ and in the absence of degeneracies in the system.⁴⁹ It also completely misses the hybridization between the molecule and the contacts,⁵⁰ which frequently results in qualitative failures.⁵¹ Thereby, the PP-NEGF approach to the Raman scattering is an important theoretical advance, because it provides a convenient way to incorporate tools of quantum chemistry and equilibrium molecular spectroscopy (traditionally formulated in the language of many-body states of an isolated molecule) into the realm of current carrying junctions.⁵²

We consider a molecule, M , bridging two metal electrodes, and subjected to an external laser radiation, rad . The electrodes act as electronic, L and R , and thermal, B , reservoirs, each at its own equilibrium. The Hamiltonian of the junction is

$$\hat{H} = \hat{H}_M + \sum_{K=L,R,B,rad} (\hat{H}_K + \hat{V}_K) \quad (1)$$

Here we represent the molecular Hamiltonian \hat{H}_M in terms of many-body states $|S\rangle$ of the molecule

$$\hat{H}_M = \sum_{S_1, S_2 \in M} H_{S_1 S_2}^{(M)} \hat{X}_{S_1 S_2} \quad (2)$$

while the Hamiltonians of the baths are expressed within second quantization

$$\begin{aligned} \hat{H}_{L(R)} &= \sum_{k \in L(R)} \varepsilon_k \hat{c}_k^\dagger \hat{c}_k, & \hat{H}_B &= \sum_{\beta \in B} \omega_\beta \hat{b}_\beta^\dagger \hat{b}_\beta, \\ \hat{H}_{rad} &= \sum_{\alpha} \nu_\alpha \hat{a}_\alpha^\dagger \hat{a}_\alpha \end{aligned} \quad (3)$$

where $\hat{X}_{S_1 S_2} = |S_1\rangle\langle S_2|$ is a Hubbard (projection) operator, and \hat{c}_k^\dagger (\hat{c}_k), \hat{b}_β^\dagger (\hat{b}_β), and \hat{a}_α^\dagger (\hat{a}_α) create (annihilate) an electron in the contacts L and R , phonon in the thermal bath B , and photon of radiation field rad , respectively. Finally, $\hat{V}_{L(R)}$, \hat{V}_B , and \hat{V}_{rad} in eq 1 describe single electron, phonon, and photon transitions between the molecule and baths

$$\hat{V}_K = \sum_{S_1, S_2 \in M} \sum_{q \in K} (V_{S_1 S_2, q}^{(K)} \hat{X}_{S_1 S_2}^\dagger \hat{O}_q + H.c.) \quad (4)$$

Here $\hat{O}_q = \hat{c}_k$, \hat{b}_β , and \hat{a}_α for $K = L(R)$, B , and rad , respectively. Below we utilize molecular vibronic states $|S_m\rangle = |e_m, \nu\rangle \approx |e_m\rangle |\nu\rangle$ as many-body basis, so that $H_{S_1 S_2}^{(M)} = \delta_{S_1 S_2} E_{S_1}$, $V_{S_1 S_2, k}^{(L(R))} = V_{e_1 e_2, k} \langle \nu_{v_1}^{(1)} | \nu_{v_2}^{(2)} \rangle$, $V_{S_1 S_2, \beta}^{(B)} = \delta_{e_1 e_2} W_{\nu_{v_1}^{(1)} \nu_{v_2}^{(2)}, \beta}$, and $V_{S_1 S_2, \alpha}^{(rad)} = -\vec{\mu}_{e_1 e_2} \vec{E}_\alpha \langle \nu_{v_1}^{(1)} | \nu_{v_2}^{(2)} \rangle$. Here $\vec{\mu}_{e_1 e_2}$ is the electronic transition dipole moment, \vec{E}_α is amplitude of the radiation field mode α , and $\langle \nu_{v_1}^{(1)} | \nu_{v_2}^{(2)} \rangle$ are overlap integrals of the vibrational wave functions for electronic ($L(R)$) and optical (rad) transitions. Corresponding Franck–Condon factors are evaluated following the method by Ruhoff and Ratner.^{53,54}

An expression for Raman scattering in current-carrying junctions was first derived considering an outgoing photon flux caused by a coherent photon scattering from an occupied initial, $\alpha = i$, to an empty final, $\alpha = f$, mode of radiation field.³⁰ The derivation was performed using a noninteracting orbital-based representation. Here, we develop a desirable generalization to the many-body molecular basis $\{|S\rangle\}$ by invoking the PP-NEGF method.^{55–58} Within this approach one can introduce pseudoparticle operator, \hat{d}_S^\dagger , that creates the molecular many-body state $|S\rangle$ by acting on vacuum state, $|S\rangle = \hat{d}_S^\dagger |0\rangle$. The methodology is identical to the second quantization. However, it is formulated in an extended Hilbert space, whose physically relevant subspace is defined by a normalization condition $\sum_S \hat{d}_S^\dagger \hat{d}_S = 1$. In the extended Hilbert space the nonequilibrium pseudoparticle Green function

$$G_{S_1 S_2}(\tau_1, \tau_2) = -i \langle T_c \hat{d}_{S_1}(\tau_1) \hat{d}_{S_2}^\dagger(\tau_2) \rangle \quad (5)$$

satisfies the usual Dyson equation. Restricting the latter to the physical subspace results in a coupled system of equations for projections of the Green function (see, e.g., ref 57 for details).

Following the line of argument of ref 30 and assuming no charge transfer (CT) contribution, an expression for intramolecular Raman flux which starts in a ground molecular state $|g\rangle$ and proceeds via set of excited states $\{|x\rangle\}$, is given by⁵⁹ (see Supporting Information for derivation details)

$$\begin{aligned}
 J(t) = 2\text{Re} \sum_{\substack{g_i, x_1, x_2, g_f \\ \bar{g}_i, \bar{x}_1, \bar{x}_2, \bar{g}_f}} \zeta_{g_i} \int_{-\infty}^t dt' \int_{-\infty}^{t'} dt_1 \int_{-\infty}^{t_1} dt_2 \\
 \Pi_{g_i, \bar{g}_i}^<(t_1 - t_2) \Pi_{g_f, \bar{g}_f}^>(t' - t) \\
 G_{\bar{x}_1, \bar{x}_2}^>(t_2, t') G_{\bar{g}_f}^>(t', t) G_{x_2, x_1}^>(t, t_1) G_{g_i, \bar{g}_i}^<(t_1, t_2)
 \end{aligned} \quad (6)$$

where $\zeta_{g_i} = 1$ (-1) when state $|g_i\rangle$ is of Fermi (Bose) type, $G_{S_1, S_2}^>/<(t_1, t_2)$ are greater/lesser projections of the Green function (5), $\Pi^{>/<}$ are greater/lesser projections of the self-energies due to coupling to radiation field. The Fourier transforms of the latter are³⁷

$$\begin{aligned}
 \Pi_{g_x, g'x}^>(\omega) &\equiv -i\Omega_{g_x, g'x}(\omega)[1 + N(\omega)] \\
 \Pi_{g_x, g'x}^<(\omega) &\equiv -i\Omega_{g_x, g'x}(\omega)N(\omega)
 \end{aligned} \quad (7)$$

where $\Omega_{g_x, g'x}(\omega) \equiv 2\pi \sum_{\alpha} V_{g_x, \alpha}^{(rad)} V_{\alpha, g'x}^{(rad)} \delta(\omega - \nu_{\alpha})$ and $N(\omega) \equiv (1/\pi) \gamma / [(\omega - \nu_i)^2 + \gamma^2]$ with ν_i being the frequency of the incoming laser radiation, γ is the laser bandwidth, and $N(\omega)$ characterizing the laser resolution. Note that eq 6 is an expression for “the normal Raman process” as discussed in refs 29 and 30. Note also that it is a time-dependent generalization similar to the CT-Raman consideration of refs.^{34,35} At steady-state eq 6 becomes $J = \int (d\omega_f) / (2\pi) J(\omega_f)$ with

$$\begin{aligned}
 J(\omega_f) = - \sum_{\substack{g_i, x_1, x_2, g_f \\ \bar{g}_i, \bar{x}_1, \bar{x}_2, \bar{g}_f}} \zeta_{g_i} \int \frac{d\omega_i}{2\pi} \int \frac{dE_i}{2\pi} \int \frac{dE_f}{2\pi} \\
 2\pi \delta(\omega_i + E_i - \omega_f - E_f) \Pi_{g_i, \bar{g}_i}^<(\omega_i) \Pi_{g_f, \bar{g}_f}^>(\omega_f) \\
 \int \frac{dE_{\bar{x}}}{2\pi} \int \frac{dE_x}{2\pi} \frac{G_{\bar{g}_f}^>(E_f) G_{\bar{x}_1, \bar{x}_2}^>(E_{\bar{x}}) G_{x_2, x_1}^>(E_x) G_{g_i, \bar{g}_i}^<(E_i)}{[\omega_i + E_i - E_{\bar{x}} - i\eta][\omega_i + E_i - E_x + i\eta]}
 \end{aligned} \quad (8)$$

where $\eta \rightarrow 0^+$ is an infinitesimal real number, $\delta(\dots)$ is the Dirac delta function. Expression 8 is convenient to use for numerical simulations as described below.

We apply the method introduced above to an OPV3 junction (see Figure 1a), which was the focus of recent Raman measurements.¹⁹ We chose parameters to be representative of a realistic experimental situation. Following refs 60–62, we assume that at low bias the main contribution to conductance comes from neutral (N) and cation (C) states of OPV3, and that $E_N^e - E_C^e - E_F = 0.05$ eV^{63,64} (here E_N^e , E_C^e , and E_F are electronic energies of neutral and cation OPV3 species, and the Fermi energy, respectively). The electron escape rates to the contacts, $\Gamma_{L(R)} \equiv 2\pi \sum_{k \in L(R)} |V_{CN, k}|^2 \delta(E - \epsilon_k)$, are taken as 15 meV in agreement with experimental estimate.⁶⁵ Molecular vibrations are modeled as harmonic oscillators (normal modes specific for cation and neutral molecule). The dissipation matrix for the vibrations due to coupling to thermal bath is assumed to be diagonal, $\Gamma_{\nu^{(m)} \nu^{(m)} + 1, \nu^{(m)} \nu^{(m)} + 1} \equiv 2\pi \sum_{\beta \in B} |W_{\nu^{(m)} \nu^{(m)} + 1, \beta}|^2 \delta(\omega - \omega_{\beta})$, and the rates are 2.5 meV. The laser field is assumed to be polarized along the principle axis of the OPV3 molecule. The intensity of the field is $\mathcal{E}_i \sim 10^{10}$ V/m, its frequency is $\nu_i = 1.4$ eV, and laser bandwidth $\gamma = 1$ meV. Temperature in the contacts is taken as 100 K. Calculations were performed on an adjustable energy grid.

Parameters of electronic and vibrational structure of the isolated molecule (ground and excited state electronic energies, normal-mode frequencies and electronic transition dipole moments of neutral and cation species) were computed with density functional theory (DFT) and time dependent DFT (TDDFT) methodologies.^{66,67} For all calculations, we use the B3LYP hybrid-functional with a 3-21+G basis set as implemented in the Gaussian'09 software package.⁶⁸

Figure 2 shows the Stokes shift of two Raman active normal modes. For the neutral OPV3 these modes are at 1199 and

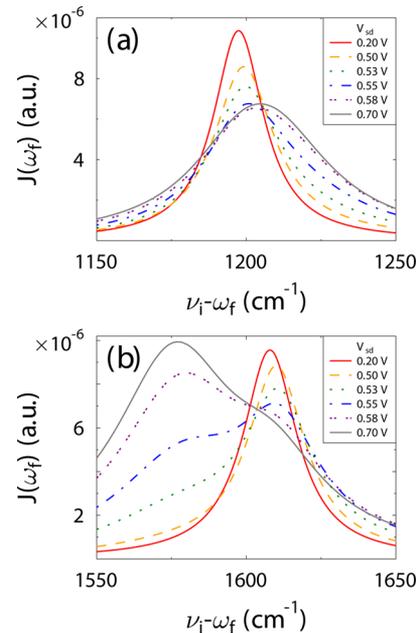


Figure 2. The Stokes peak, eq 8, versus Raman shift for several source-drain biases, V_{sd} . Shown are results for molecular vibrational modes at (a) 1199 and (b) 1608 cm^{-1} . See text for parameters used for simulations.

1608 cm^{-1} with displacements schematically shown in Figure 1b,c. Oxidation of the molecule leads to shift of the modes to 1211 and 1577 cm^{-1} , respectively. Under finite bias both neutral and cation species contribute to the total Raman signal, with the latter contribution becoming more pronounced at higher bias. Correspondingly, the Stokes peak shifts to higher or lower frequencies for the two modes. Note that calculation in Figure 2a employs $\nu_i = 1.2$ eV as frequency of the laser field. Note also that the shift for the mode at 1608 cm^{-1} (see Figure 2b) was observed experimentally^{16,19} and discussed theoretically within a perturbation theory analysis of electron-vibration coupling.⁶⁹ At finite bias charge transfer between the molecule and contacts induces dissipation in the ground states of the neutral and cation species, which leads to broadening of the peaks. We note that the PP-NEGF approach is especially convenient for describing this system since it easily accounts for the different vibrational frequencies of the neutral and cation species while retaining information on mixture of molecular states with those of the contacts. This allows for high accuracy treatment of the electron-vibration coupling in junction which goes far beyond usual considerations within perturbation theory.^{37,57}

Dependence of the anti-Stokes peak on bias is shown in Figure 3a. In addition to the shift of the peak position, as discussed above, heating of the vibration by electric flux results

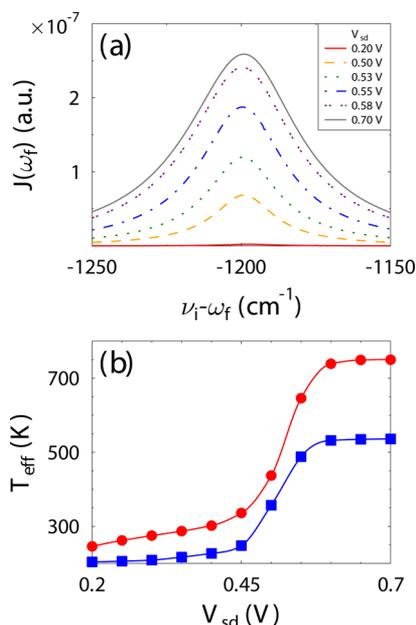


Figure 3. Bias-induced vibrational heating. Shown are (a) the anti-Stokes peak, eq 8, of molecular vibration at 1199 cm^{-1} versus Raman shift for several source-drain biases, V_{sd} . (b) Effective temperature versus applied bias for molecular vibrational modes at 1608 cm^{-1} (squares, blue) and 1199 cm^{-1} (circles, red). See text for parameters used for simulations.

in an increase of the anti-Stokes peak amplitude at higher bias, as is observed in the experiment.¹⁹ It is interesting to note that the shift in the anti-Stokes line is smaller than that of the Stokes peak. While in general there are a number of reasons for such shifts (for example, Stark effect or shift of the line induced by the molecule-contacts hybridization), here we argue that the main contribution comes from renormalization of molecular vibration under oxidation. Thus the shift under bias is defined by relative contributions from neutral molecule and cation to the total Raman signal. In a simplified picture, these contributions to Stokes and anti-Stokes lines are proportional to populations of the ground and excited states of the to species, respectively. Bias-induced transfer of electronic population probability from vibronic states of neutral molecule to those of the cation is proportional to the corresponding Franck–Condon factors. The latter are stronger for ground state, which results in more pronounced shift in the Stokes line. We note that different shifts of the Stokes and anti-Stokes lines with bias are consistent with the experimental data (see Figure 3b in ref 19).

While the temperature of nonequilibrium system is not defined, the notion of “effective temperature” is often utilized in experiments to characterize the extent of bias induced heating in the molecule.^{17–19} In particular, effective vibrational temperature, describing extent of vibrational excitation by electron flux, may be estimated from spectroscopic data utilizing ratio of anti-Stokes to Stokes peaks as

$$\frac{J(\nu_i + \omega_v)}{J(\nu_i - \omega_v)} \approx e^{-\hbar\omega_v/k_B T_{\text{eff}}} \quad (9)$$

(here ω_v is frequency of the normal mode of the neutral molecule). Figure 3b displays result of this estimate. Note that the calculated effective temperature is in agreement with the experimental data (compare with Figure 3a in ref 19).

In conclusion, we presented a pseudoparticle formulation for Raman spectroscopy in molecular junctions. This framework allows us to describe open nonequilibrium molecular system in the language of many-body states of the isolated molecule. The method treats all intramolecular interactions exactly, while also keeping the information on hybridization between molecular states and those of the contacts, and on the nonequilibrium electronic population in the molecule. We further applied this methodology to simulate the Raman response of the OPV3 molecular junction under bias, where high quality experimental data recently became available. Parameters of the electronic and vibrational structure of the molecule were obtained from DFT and TDDFT quantum-chemical calculations and from experimental data. Our modeling results demonstrate a shift to lower frequencies and broadening of the Stokes line, reproducing the experimental trends. We argue that such a shift may be caused by the cation contribution to Raman scattering, and that in principle also a shift of the line to higher frequencies may be observable. Our estimate of vibrational heating caused by electric current is also in agreement with experimental data. Thus presented PP-NEGF methodology provides a convenient way to incorporate electronic information obtained for an isolated molecule in equilibrium with convectional quantum-chemical tools to simulate nonequilibrium dynamics of current carrying junctions. We believe that the developed method constitutes an important step toward full ab initio calculations of optical response in molecular junctions.

■ ASSOCIATED CONTENT

Supporting Information

Derivation of eq 6 and computational details (OPV3 chemical and electronic structure, and information on normal modes) are provided. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: migalperin@ucsd.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We gratefully acknowledge support by the Department of Energy (M.G., Early Career Award, DE-SC0006422) and the Center for Integrated Nanotechnologies (CINT) at Los Alamos National Laboratory (LANL). LANL is operated by Los Alamos National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC5206NA25396.

■ REFERENCES

- (1) Aviram, A.; Ratner, M. A. *Chem. Phys. Lett.* **1974**, *29*, 277–283.
- (2) Fleischmann, M.; Hendra, P.; McQuillan, A. *Chem. Phys. Lett.* **1974**, *26*, 163–166.
- (3) Jeanmaire, D. L.; Van Duyne, R. P. *J. Electroanal. Chem.* **1977**, *84*, 1–20.
- (4) Nie, S.; Emory, S. R. *Science* **1997**, *275*, 1102–1106.
- (5) Kneipp, K.; Wang, Y.; Kneipp, H.; Perelman, L. T.; Itzkan, I.; Dasari, R. R.; Feld, M. S. *Phys. Rev. Lett.* **1997**, *78*, 1667–1670.
- (6) Qian, X.-M.; Nie, S. M. *Chem. Soc. Rev.* **2008**, *37*, 912–920.
- (7) Wustholz, K. L.; Brosseau, C. L.; Casadio, F.; Van Duyne, R. P. *Phys. Chem. Chem. Phys.* **2009**, *11*, 7350–7359.

- (8) Sharma, B.; Frontiera, R. R.; Henry, A.-I.; Ringe, E.; Duyne, R. P. *V. Mater. Today* **2012**, *15*, 16–25.
- (9) Moskovits, M. *Phys. Chem. Chem. Phys.* **2013**, *15*, 5301–5311.
- (10) Kleinman, S. L.; Frontiera, R. R.; Henry, A.-I.; Dieringer, J. A.; Van Duyne, R. P. *Phys. Chem. Chem. Phys.* **2013**, *15*, 21–36.
- (11) Michaels, A. M.; Jiang, J.; Brus, L. *J. Phys. Chem. B* **2000**, *104*, 11965–11971.
- (12) Ward, D. R.; Grady, N. K.; Levin, C. S.; Halas, N. J.; Wu, Y.; Nordlander, P.; Natelson, D. *Nano Lett.* **2007**, *7*, 1396–1400.
- (13) Banik, M.; Nag, A.; El-Khoury, P. Z.; Rodriguez Perez, A.; Guarrotxena, N.; Bazan, G. C.; Apkarian, V. A. *J. Phys. Chem. C* **2012**, *116*, 10415–10423.
- (14) Shamaï, T.; Selzer, Y. *Chem. Soc. Rev.* **2011**, *40*, 2293–2305.
- (15) Galperin, M.; Nitzan, A. *Phys. Chem. Chem. Phys.* **2012**, *14*, 9421–9438.
- (16) Natelson, D.; Li, Y.; Herzog, J. B. *Phys. Chem. Chem. Phys.* **2013**, *15*, 5262–5275.
- (17) Ioffe, Z.; Shamaï, T.; Ophir, A.; Noy, G.; Yutsis, I.; Kfir, K.; Cheshnovsky, O.; Selzer, Y. *Nat. Nanotechnol.* **2008**, *3*, 727–732.
- (18) Ward, D. R.; Halas, N. J.; Ciszek, J. W.; Tour, J. M.; Wu, Y.; Nordlander, P.; Natelson, D. *Nano Lett.* **2008**, *8*, 919–924.
- (19) Ward, D. R.; Corley, D. A.; Tour, J. M.; Natelson, D. *Nat. Nanotechnol.* **2011**, *6*, 33–38.
- (20) Liu, Z.; Ding, S.-Y.; Chen, Z.-B.; Wang, X.; Tian, J.-H.; Anema, J. R.; Zhou, X.-S.; Wu, D.-Y.; Mao, B.-W.; Xu, X.; Ren, B.; Tian, Z.-Q. *Nat. Commun.* **2011**, *2*, 305.
- (21) Jiang, N.; Foley, E. T.; Klingsporn, J. M.; Sonntag, M. D.; Valley, N. A.; Dieringer, J. A.; Seideman, T.; Schatz, G. C.; Hersam, M. C.; Van Duyne, R. P. *Nano Lett.* **2012**, *12*, 5061–5067.
- (22) El-Khoury, P. Z.; Hu, D.; Apkarian, V. A.; Hess, W. P. *Nano Lett.* **2013**, *13*, 1858–1861.
- (23) Matsuhita, R.; Horikawa, M.; Naitoh, Y.; Nakamura, H.; Kiguchi, M. *J. Phys. Chem. C* **2013**, *117*, 1791–1795.
- (24) Banik, M.; El-Khoury, P. Z.; Nag, A.; Rodriguez-Perez, A.; Guarrotxena, N.; Bazan, G. C.; Apkarian, V. A. *ACS Nano* **2012**, *6*, 10343–10354.
- (25) Zhang, R.; Zhang, Y.; Dong, Z. C.; Jiang, S.; Zhang, C.; Chen, L. G.; Zhang, L.; Liao, Y.; Aizpurua, J.; Luo, Y.; Yang, J. L.; Hou, J. G. *Nature* **2013**, *498*, 82–86.
- (26) Banik, M.; Apkarian, V. A.; Park, T.-H.; Galperin, M. *J. Phys. Chem. Lett.* **2013**, *4*, 88–92.
- (27) Konishi, T.; Kiguchi, M.; Takase, M.; Nagasawa, F.; Nabika, H.; Ikeda, K.; Uosaki, K.; Ueno, K.; Misawa, H.; Murakoshi, K. *J. Am. Chem. Soc.* **2013**, *135*, 1009–1014.
- (28) Chen, H.; Schatz, G. C.; Ratner, M. A. *Rep. Prog. Phys.* **2012**, *75*, 096402.
- (29) Galperin, M.; Ratner, M. A.; Nitzan, A. *Nano Lett.* **2009**, *9*, 758–762.
- (30) Galperin, M.; Ratner, M. A.; Nitzan, A. *J. Chem. Phys.* **2009**, *130*, 144109.
- (31) Galperin, M.; Nitzan, A. *J. Phys. Chem. Lett.* **2011**, *2*, 2110–2113.
- (32) Galperin, M.; Nitzan, A. *Phys. Rev. B* **2011**, *84*, 195325.
- (33) Oren, M.; Galperin, M.; Nitzan, A. *Phys. Rev. B* **2012**, *85*, 115435.
- (34) Park, T.-H.; Galperin, M. *Europhys. Lett.* **2011**, *95*, 27001.
- (35) Park, T.-H.; Galperin, M. *Phys. Rev. B* **2011**, *84*, 075447.
- (36) Park, T.-H.; Galperin, M. *Phys. Scr., T* **2012**, *151*, 014038.
- (37) White, A. J.; Fainberg, B. D.; Galperin, M. *J. Phys. Chem. Lett.* **2012**, *3*, 2738–2743.
- (38) Jensen, L.; Aikens, C. M.; Schatz, G. C. *Chem. Soc. Rev.* **2008**, *37*, 1061–1073.
- (39) Dieringer, J. A.; Wustholz, K. L.; Masiello, D. J.; Camden, J. P.; Kleinman, S. L.; Schatz, G. C.; Van Duyne, R. P. *J. Am. Chem. Soc.* **2009**, *131*, 849–854.
- (40) Morton, S. M.; Jensen, L. *J. Am. Chem. Soc.* **2009**, *131*, 4090–4098.
- (41) Chen, H.; McMahon, J. M.; Ratner, M. A.; Schatz, G. C. *J. Phys. Chem. C* **2010**, *114*, 14384–14392.
- (42) Zhao, L.-B.; Huang, R.; Huang, Y.-F.; Wu, D.-Y.; Ren, B.; Tian, Z.-Q. *J. Chem. Phys.* **2011**, *135*, 134707.
- (43) Payton, J. L.; Morton, S. M.; Moore, J. E.; Jensen, L. *J. Chem. Phys.* **2012**, *136*, 214103.
- (44) Mullin, J.; Schatz, G. C. *J. Phys. Chem. A* **2012**, *116*, 1931–1938.
- (45) Zhao, L. L.; Jensen, L.; Schatz, G. C. *Nano Lett.* **2006**, *6*, 1229–1234.
- (46) Zhao, X.; Liu, S.; Li, Y.; Chen, M. *Spectrochim. Acta, Part A* **2010**, *75*, 794–798.
- (47) Mirjani, F.; Thijssen, J. M.; Ratner, M. A. *J. Phys. Chem. C* **2012**, *116*, 23120–23129.
- (48) Leijnse, M.; Wegewijs, M. R. *Phys. Rev. B* **2008**, *78*, 235424.
- (49) Schultz, M. G.; von Oppen, F. *Phys. Rev. B* **2009**, *80*, 033302.
- (50) Esposito, M.; Galperin, M. *Phys. Rev. B* **2009**, *79*, 205303.
- (51) Esposito, M.; Galperin, M. *J. Phys. Chem. C* **2010**, *114*, 20362–20369.
- (52) A more detailed discussion of advantages of the PP-NEGF formulation for Raman scattering in junctions is given in the Supporting Information.
- (53) Ruhoff, P. T. *Chem. Phys.* **1994**, *186*, 355–374.
- (54) Ruhoff, P. T.; Ratner, M. A. *Int. J. Quantum Chem.* **2000**, *77*, 383–392.
- (55) Eckstein, M.; Werner, P. *Phys. Rev. B* **2010**, *82*, 115115.
- (56) Oh, J. H.; Ahn, D.; Bubanja, V. *Phys. Rev. B* **2011**, *83*, 205302.
- (57) White, A. J.; Galperin, M. *Phys. Chem. Chem. Phys.* **2012**, *14*, 13809–13819.
- (58) Marbach, J.; Bronold, F. X.; Fehske, H. *Phys. Rev. B* **2012**, *86*, 115417.
- (59) In our approach, we extend ideas of atomic limit formulations to nonequilibrium regime, where the starting point of treatment is an isolated system, and coupling between the system and baths is taken into account within a perturbation theory. Thus ground and excited states used in our method are many-body states of the isolated molecule.
- (60) Crljen, Ž.; Grigoriev, A.; Wendin, G.; Stokbro, K. *Phys. Rev. B* **2005**, *71*, 165316.
- (61) Stokbro, K. *J. Phys.: Condens. Matter* **2008**, *20*, 064216.
- (62) Bilić, A.; Crljen, Ž.; Gumhalter, B.; Gale, J. D.; Rungger, I.; Sanvito, S. *Phys. Rev. B* **2010**, *81*, 155101.
- (63) Hybertsen, M. S.; Venkataraman, L.; Klare, J. E.; Whalley, A. C.; Steigerwald, M. L.; Nuckolls, C. *J. Phys.: Condens. Matter* **2008**, *20*, 374115.
- (64) Das, B. *AIP Conf. Proc.* **2011**, *1349*, 951–952.
- (65) Poot, M.; Osorio, E.; O'Neill, K.; Thijssen, J. M.; Vanmaekelbergh, D.; Walree, C. A. v.; Jenneskens, L. W.; van der Zant, H. S. J. *Nano Lett.* **2006**, *6*, 1031–1035.
- (66) Parr, R. G.; Yang, W. *Density-Functional Theory of Atoms and Molecules*; Oxford University Press: New York, 1989.
- (67) Ullrich, C. A. *Time-Dependent Density-Functional Theory*; Oxford University Press: New York, 2012.
- (68) Frisch, M. J. et al. *Gaussian 09*, rev. D.01; Gaussian Inc.: Wallingford, CT, 2009.
- (69) Kaasbjerg, K.; Novotný, T.; Nitzan, A. *Phys. Rev. B* **2013**, *88*, 201405.