Introducing Ionic and/or Hydrogen Bonds into the SAM//Ga$_2$O$_3$ Top-Interface of Ag^{TS}/S(CH$_2$)$_n$T//Ga$_2$O$_3$/EGaIn Junctions

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⑤ Supporting Information

ABSTRACT: Junctions with the structure Ag^{TS}/S(CH$_2$)$_n$T//Ga$_2$O$_3$/EGaIn (where S(CH$_2$)$_n$T is a self-assembled monolayer, SAM, of n-alkanethiolate bearing a terminal functional group T) make it possible to examine the response of rates of charge transport by tunneling to changes in the strength of the interaction between T and Ga$_2$O$_3$. Introducing a series of Lewis acidic/basic functional groups (T = −OH, −SH, −CO$_2$H, −CONH$_2$, and −PO$_3$H) at the terminus of the SAM gave values for the tunneling current density, $J(V)$ in A/cm^2, that were indistinguishable (i.e., differed by less than a factor of 3) from the values observed with n-alkanethiolates of equivalent length. The insensitivity of the rate of tunneling to changes in the terminal functional group implies that replacing weak van der Waals contact interactions with stronger hydrogen- or ionic bonds at the

T//Ga$_2$O$_3$ interface does not change the shape (i.e., the height or width) of the tunneling barrier enough to affect rates of charge transport. A comparison of the injection current, J_0, for T = −CO$_2$H, and T = −CH$_2$CH$_3$—two groups having similar extended lengths (in Å, or in numbers of non-hydrogen atoms)—suggests that both groups make indistinguishable contributions to the height of the tunneling barrier.

KEYWORDS: Tunneling, charge transport, self-assembled monolayers, EGaIn, molecular electronics, interfaces
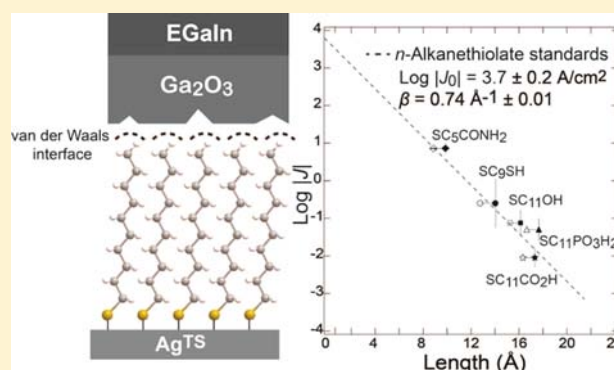
Studies of the electrical behavior of junctions based on self-assembled monolayers, SAMs, and having the structure Ag^{TS}/S(CH$_2$)$_n$T//Ga$_2$O$_3$/EGaIn have revealed several surprising insensitivities of the rates of charge transport across the SAM to the structure of the terminal group (T) of the SAM.[1−5] (Here, Ag^{TS} indicates a template-stripped silver substrate,[6] EGaIn is eutectic gallium indium alloy, and Ga$_2$O$_3$ is a surface oxide that forms at the surface of EGaIn almost immediately upon exposure to air,[7] "/" refers to an ionic or covalent interface, and "//" indicates a van der Waals interface.) One current interest in the interpretation of data for charge transport obtained with EGaIn top-electrodes is the contribution of the noncovalent van der Waals T//Ga$_2$O$_3$ top-interface to the shape of the tunneling barrier. When the group T is aliphatic, simple aromatic, or polar but not strongly Lewis-acidic or Lewis-basic—a range of groups differing widely in electronic and molecular structure—details of the atomic/electronic structure of the group seem relatively unimportant and the contribution of T to the rate of tunneling appears to come primarily from its contribution to the width of the barrier.[4,5,8] In (possible) contrast, n-alkanethiolates show an odd/even effect[9] (which might be a reflection of interfacial

structure); T = ferrocene (a redox active group that changes the mechanism of charge transport from tunneling to a combination of hopping and tunneling at a negative applied bias) and its derivatives produce large rectification ratios ($R > 100$).[10−14] Certain terminal groups (in other systems) have also been reported to have large influences on tunneling currents.[15−20] To rationalize these results, this work systematically examined T groups capable of interacting with the surface of Ga$_2$O$_3$ with strengths between van der Waals and covalent bonds and determined whether these groups (and the strengths of their interactions with the top Ga$_2$O$_3$/EGaIn electrode) changed rates of tunneling.

We have introduced a series of protic polar groups (T = −CO$_2$H, −SH, −PO$_3$H$_2$, −OH, −CONH$_2$) into the interface between the electrically conducting Ga$_2$O$_3$ layer[8] and the insulating methylene (−(CH$_2$)$_n$−) portion of the SAM. In principle, these polar groups are capable of interacting with the

surface of the Ga_2O_3 either as Lewis acids or bases and, thus, more strongly than the aprotic polar T groups,[4] and the nonpolar aromatic and aliphatic T groups we have studied before.[5] We focused on two particular questions: (i) Do these Lewis acidic or basic groups at the $T//Ga_2O_3$ interface change the current density (J in A/cm^2 at applied bias V) through these junctions? (ii) How do these changes in structure affect the apparent dependence of the charge injection current density (J_0), and the tunneling decay constant (β) (as defined by the simplified Simmons equation[21] for tunneling, eq 1)?

$$J(V) = J_0(V)e^{-\beta d} = J_0(V)10^{-\beta d/2.303} \tag{1}$$

A tunneling junction of the form $Ag^{TS}/A(CH_2)_nT//Ga_2O_3/$ EGaIn has two different interfaces: (i) a covalent or ionic so-called "bottom" interface between the anchoring atom A and the Ag,[TS] and (ii) a van der Waals interface between T and the Ga_2O_3. The structure of the anchoring group (A) has little influence on the rate of tunneling (for example, replacing $Ag^{TS}/$ $S(CH_2)_nCH_3$ with $Ag^{TS}/O_2C(CH_2)_{n-1}CH_3$ does not significantly change this rate).[2] The effect of structural variations at the top interface—where the strength of the interaction between the T and Ga_2O_3, in principle, could change from a weak physical interaction (i.e., van der Waals interaction) to a much stronger chemical bond—is a question relevant to the relationship between the molecular-level structure of the SAM and its properties as a tunneling barrier.

This paper follows a physical–organic design in studying charge transport across EGaIn-based junctions; that is, we varied only the structure of the terminal group T, while keeping other components of the SAM (i.e., its thiolate anchoring group and polymethylene backbone ($-(CH_2)_n-$) and the electrodes) the same. This strategy minimized changes in the structure of the SAM unrelated to the group T and the $T//Ga_2O_3$ interface. (It cannot, of course, entirely eliminate them, since the structure of the group T may influence the structure of the polymethylene unit). We incorporated various terminal groups T into these junctions, and analyzed trends in $J(V)$ with T, assuming that the contributions of all other components of the junction remained consistent with those well-established for n-alkanethiolates. We chose the Lewis acidic/basic groups ($-SH$, $-OH$, $-CONH_2$, $-CO_2H$, and $-PO_3H_2$) based on their ability, in principle, to interact chemically (i.e., using interactions beyond electrostatic contacts, by hydrogen bonding, coordination, or formation of covalent bonds) with the gallium oxide of the top-electrode. The relevant values of pK_a, in water, for these groups are $-PO_3H_2 = 2.4$ (pK_{a1}), 7.1 (pK_{a2}); $-CO_2H = 4.8$; $-SH = 10.3$; $-OH = 18$; $-CONH_2 = 25$.[22]

The structural and electrical characteristics of the $Ag^{TS}/$ $S(CH_2)_nT//Ga_2O_3/EGaIn$ junction are, by now, generally well-established.[7,8,10,23−26] In prior work, we concluded that (i) the resistance of the Ga_2O_3 film does not contribute significantly to the resistance of the junction;[7,8,23,24,27] (ii) the surface of the film of a "conical tip"[24] electrode is rough, and only a small (although reproducible) fraction ($\sim10^{-4}$) of the apparent geometrical area of contact (as estimated by microscopy) between $Ga_2O_3/EGaIn$ tip and the SAM is in effective electrical contact.[8]

The rate of charge transport in these junctions is compatible with a model based on hole transport through a potential barrier provided by the electrically insulating SAM, and the interfaces between top- and bottom-electrodes.[19,28] We have

roughly estimated the shape of this potential barrier using known values of work functions for silver (-4.5 eV relative to vacuum)[29] and EGaIn (-4.3 eV).[7] For a cluster of n-alkanethiolates (n-decanethiolate, SC_{10}) bound to Ag, we used density functional theory (DFT) to estimate the values of the frontier orbital energies—the highest occupied molecular orbital, HOMO (-4.89 eV), and lowest unoccupied molecular orbital, LUMO (-2.92 eV). Table S1 (in the Supporting Information) summarizes the potentials calculated for n-alkanethiolates and ω-carboxyl-alkanethiolates on Ag.

In a molecular junction, the width of the tunneling barrier (d, eq 1) is commonly approximated by the length of the molecules comprising the SAM that separates the two electrodes, but it is still unclear which components of the molecule should be considered to belong to the insulating tunneling barrier. The tunneling barrier certainly includes all of the insulating $-(CH_2)_n-$ units, but it might also include the anchoring atom (S), and the terminal group T in van der Waals contact with Ga_2O_3. We do not know with precision the shape (height and width of the energy profile) of the barrier associated with a van der Waals interface between group T and Ga_2O_3; we assume that it is the highest potential in the barrier (potentially close to vacuum at 0 eV). As a starting point in the analysis of the width of the barrier, we defined the injection current for $d = 0$ Å to be that obtained by extrapolation of a series of n-alkanethiolates $S(CH_2)_nH$ ($n =$ 16 to $n = 0$), and included both the anchoring atom and the distal hydrogen atom (Figure 1).

We fabricated "unflattened" conical-tip EGaIn electrodes and selected those that were free of visible surface asperities (using procedures described elsewhere,[8] and in the Supporting Information) to measure current density, $J(V)$, across T-terminated alkanethiolates on Ag^{TS}. Figure 2 shows $J(V)$ data for T being either a methyl group (T = $-CH_3$)—represented by the dashed reference line—or a Lewis acid/base functional group. We do not know the ionization state of the protic groups T in the SAM, and arbitrarily assume a protonated state for each SAM when calculating the total molecular length (from the anchoring atom to the very distal hydrogen atom). In order to account for uncertainty associated with protonation state and molecular length, the horizontal bar for each point in Figure 2 includes estimated lengths of both protonated and deprotonated states. The Supporting Information (Figure S5) contains a summary of the histograms describing all measurements of $\log|J|$ ($V = +0.5$ V). The values of J ($V = +0.5$ V) for alkanethiolates terminated with protic groups T were not significantly different from the methyl-terminated alkanethiolates (i.e., they differ by less than a factor of 3); an additional analysis of the data at a lower bias ($V = +0.2$ V) revealed the same trend (Supporting Information Figure S7). This result suggests that introducing Lewis-acidic or -basic groups that have the potential to coordinate gallium oxide or hydroxide in the $T//Ga_2O_3$ interface does not change the shape of the barrier enough to affect the tunneling conductance of the junctions.

Although we have no quantitative measure of the strength of the interaction between EGaIn and the surface of the SAM, we have one clear qualitative indication that the interaction is stronger for T = $-CO_2H$ than for T = $-CH_3$. Upon retraction of the EGaIn conical tip electrode from the surface (for T = $-CO_2H$, Supporting Information Figure S2), the tip adhered to the SAM. Although this tip is "sticky" (and thus, we infer, interacts with stronger bonds with the surface of the SAM than
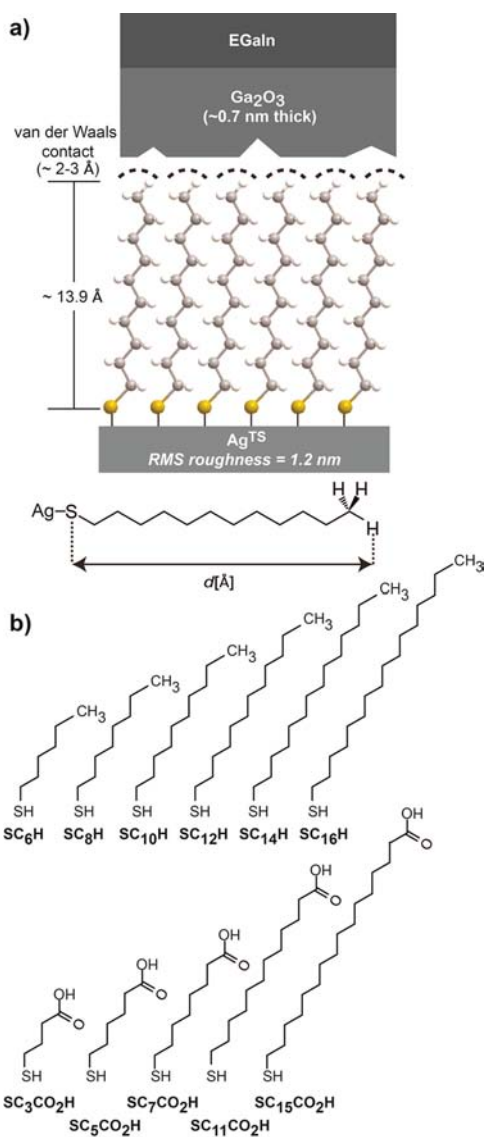
Figure 1. (a) Components of the $Ag^{TS}/S(CH_2)_n T//Ga_2O_3/EGaIn$ junction, where n is the number of methylene units (CH_2), and T is a terminal functional group; here $n = 9$ and T = CH_3. A tilt angle of $11°$ from the surface normal was applied to the SAM.[39] The inherent roughness of the Ga_2O_3 film and the SAM-bound Ag^{TS} substrate contributes to an effective electrical contact area that is $\sim 10^{-4}$ the geometrical contact area.[8] The van der Waals contact distance was estimated by adding the van der Waals radius of the terminal H atom of the SAM and the O atom of the Ga_2O_3 film. We do not know the height or width of the energy profile associated with the van der Waals interface. Definition of the molecular length in Å of the insulating molecular component from an all trans-extended configuration using Chem3D software. The distance is calculated from the center of the sulfur anchoring atom to the center of the distal hydrogen atom that is presumably closest to the EGaIn top electrode. (b) A series of methyl- and carboxyl-terminated alkanethiolates used to form SAMs for the determination of J_0 and β.

Figure 2. $\langle \log|J| \rangle$ at +0.5 V versus molecular length for n-alkanethiolate standards and alkanethiolates bearing terminal Lewis acidic or basic functional groups. The two points for protonated (●) or deprotonated (○) ω-substituted-alkanethiolate SAM take into account the difference in the estimated molecular length associated with the protonation state of the SAM (right point, protonated state; left point, deprotonated). The molecular length was estimated using an all trans-extended configuration from the sulfur atom to the final hydrogen atom using Chem3D software.

bonds do not change the rate of charge transport detectably. The inference that Ga_2O_3 can act as a base (i.e., a hydrogen bond acceptor) agrees with work by Ito and co-workers.[30] We infer that a terminal T = $-CO_2H$ group forms bonds with the Ga_2O_3 of the top-electrode that are stronger than van der Waals interactions involving T = $-CH_3$ and other groups, but that these bonds do not increase observably the tunneling current relative to a top interface having the weak van der Waals interaction of a T = $-CH_3$ group.[31,32]

To investigate further the influence of the interaction between T = $-CO_2H$ and the Ga_2O_3 of the EGaIn top electrode on the rate of charge transport, we investigated a range of lengths of ω-carboxyl-alkanethiolates (Figure 3). The Supporting Information contains histograms of data for log |J| for carboxyl-terminated molecules. Yields of working junctions for the carboxyl-terminated SAMs (100%) were as high or higher than those composed of n-alkanethiolates. Standard deviations of measured currents for ω-carboxyl-alkanethiolates were smaller than those of the n-alkanethiolates; the $\sigma_{\log}$ calculated from the Gaussian fitting was ~ 0.3 for SAMs bearing terminal carboxyl groups, but ~ 0.5 for SAMs of n-alkanethiolates on Ag^{TS} (Supporting Information Figure S5 and S6). We note that $\sigma_{\log} \sim 0.3$ indicates that $\sim 67\%$ of the junctions give values of J (V = +0.5 V) that fall within a range differing by a factor of 4 (across multiple junctions, tips, and users). This narrow distribution indicates that EGaIn-based junctions based on a T//Ga_2O_3 contact are reproducible and replicable and suggests that the formation of a weak bond at the SAM//Ga_2O_3 interface increases the stability of the junction on measurements of $J(V)$.

To determine the contribution of a terminal carboxyl group (T = $-CO_2H$) to the shape (the height and width) of the tunneling barrier, we compared the tunneling current densities with length-matched n-alkanethiolates (T = $-CH_3$). We estimated the width, d, of the tunneling barrier using the following three different assumptions (Figures 3 and 4): (i) $d[\text{Å}]$ = the total length of the molecular SAM in Å, from the

other surfaces we have examined; for example, the surface of n-alkanethiolates on Ag), the measured current density is indistinguishable from n-alkanethiolate standards of the same length. Moreover, the adhesion does not result in electrically "shorted" junctions. This observation suggests qualitatively that, at least in part, terminal CO_2H groups form hydrogen or coordination bonds with the gallium oxide, but that these
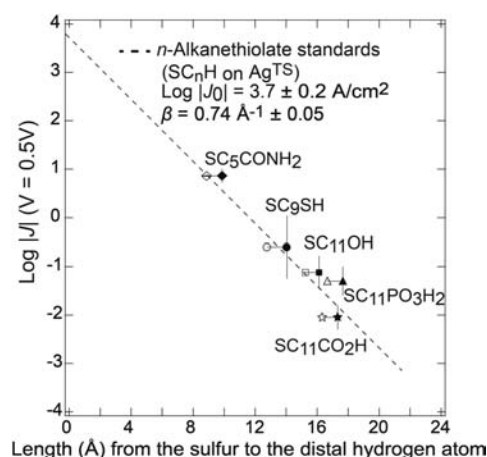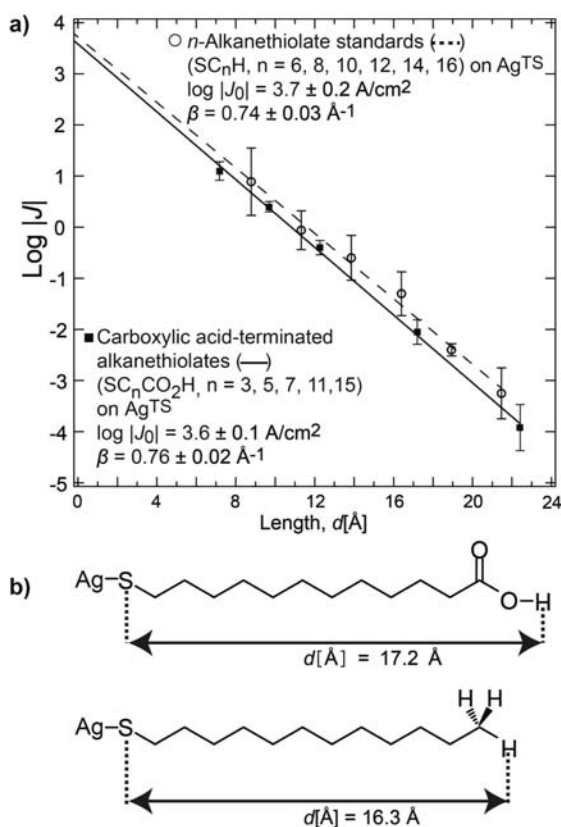
Figure 3. (a) Plot of the Gaussian mean values of $\log|J|$ at $+0.5$ V versus molecular length (calculated in Å for an all trans-extended conformation) for ω-carboxyl-alkanethiolates and n-alkanethiolate standards on Ag^{TS}. The least-squares lines are not distinguishable. (b) The distance is calculated from the sulfur atom to the final hydrogen atom as shown.

center of the anchoring atom (sulfur) to the center of the distal atom assumed to be closest to the top electrode. Thus, for example, $d[Å]$ for $S(CH_2)_{10}H$ would be 12.9 Å for the S to C distance of the $(CH_2)_{10}$ unit, plus 1.0 Å for the terminal hydrogen; that for $S(CH_2)_9CO_2H$ would be 11.8 Å for the S to C distance of the $(CH_2)_9$ unit, plus 3.1 Å for T $= -CO_2H$. (ii) $d[S(CH_2)_nT]$ = the sum of the number of methylene (CH_2) units, the anchoring atom (here S), and the non-hydrogen atoms of the terminal functional group, (thus, for example, $d[S(CH_2)_nT]$ for $S(CH_2)_{10}H$ would be 10 methylene units and 1 sulfur atom; that for $S(CH_2)_9CO_2H$ would be 9 methylene units, 1 sulfur atom, and 2 non-hydrogen atoms, C and O, from T). (iii) $d[(CH_2)_n]$ is determined only by the number of methylene (CH_2) units, (thus, for example, $d[(CH_2)_n]$ for $S(CH_2)_{10}H$ would be 10 methylene and that for S-$(CH_2)_9CO_2H$ would be 9 methylene units).

Figure 3 shows a plot of $\log|J(+0.5\ V)|$ versus $d[Å]$ for different lengths of carboxyl-terminated alkanethiolates, and for n-alkanethiolate standards (dashed line). The linear-least-squares fit ($R^2 = 0.99$) of $\langle\log|J(+0.5\ V)|\rangle$ to eq 1[21,33] yielded the injection current ($\log|J_0(+0.5\ V)|$) and the tunneling attenuation coefficient (β, Å^{-1}). The injection current for the carboxyl-terminated alkanethiolates ($\log|J_0(0.5\ V)| = 3.6 \pm 0.2$ A/cm^2) was indistinguishable from that of the methyl terminated n-alkanethiolate standards ($\log|J_0(0.5\ V)| = 3.7 \pm 0.2$ A/cm^2) when considering the entire length (measured in Å) of the SAM from the sulfur atom to the distal hydrogen atom of the carboxyl group in contact with Ga$_2$O$_3$.

The Simmons equation (eq 1) fits the experimental observations (Figure 3) qualitatively in this experiment (as in many other experiments).[8,34,35] There are, however, unresolved questions in most of these experiments about the interpretation of the parameters J_0, β, and d. The attenuation parameter β describes the falloff in tunneling current with distance, and is remarkably consistent ($\beta = 0.73-0.89$ Å^{-1} or $0.9-1.1$ nC^{-1}) for a large number of studies of n-alkanethiolates on gold and silver, and of n-alkyl groups bonded directly to silicon.[28,34−38] The value of the injection current, J_0, is interpreted to be characteristic of a hypothetical junction in which the SAM has zero length d, but in which the characteristics of the Ag/S and T//Ga$_2$O$_3$ interfaces are preserved. For all compounds (other than those with $(CH_2)_n$ groups so short that the AgS and T groups interact directly), we expected the contribution to J_0 from the Ag/S interface to be the same for all experimental junctions of the form Ag/S$(CH_2)_n$T//Ga$_2$O$_3$/EGaIn. For compounds where T is not a methyl group, however, there is a question about the meaning of d (a parameter that defines the width of the tunneling barrier): namely, should T be considered as part of the insulating tunneling barrier, or a part of the electrically conducting Ga$_2$O$_3$ interface, or as some hybrid between the two? To address this question, we have plotted $J(V)$ as a function of the number of non-hydrogen atoms (here, S and C and/or O) and as a function only of the number of methylene groups in the molecules of the junction. Figure 4a shows that the former plot yields effectively indistinguishable least-squares fits for the trend derived from SAMs of ω-carboxyl-alkanethiolates and from SAMs of n-alkanethiolates with the same value of J_0 at 0.5 V; the latter yields parallel lines, but quite different values of J_0. These data are compatible with the conclusion that the contribution of the carboxyl group to the width of the tunneling barrier is equivalent to that of an ethyl ($-CH_2CH_3$) group, and not to that of a group whose electronic properties make it part of the electronically conducting part of the interface, or one that changes the shape of the tunneling barrier (relative to T $= -CH_3$ of n-alkanethiolates) in a way that significantly (at the resolution of our experiments) influences tunneling currents.

The value of β for the carboxyl-terminated SAMs ($\beta = 0.74 \pm 0.02$ Å^{-1}, 0.94 ± 0.05 n$_{CH2}^{-1}$) is also indistinguishable from that of the n-alkanethiolate standards ($\beta = 0.78 \pm 0.03$ Å^{-1}, 0.92 ± 0.04 n$_{CH2}^{-1}$). This similarity in the tunneling decay coefficient suggests that the attenuation in tunneling current through the SAM is not substantially influenced by the chemical nature of the top interface, or of the electrical dipoles that we associate with these polar groups T, over the range of compounds summarized in Figures 2 and 3.

We conclude that replacing a terminal n-alkyl group (T) of an n-alkanethiolate of the same total length (e.g., T $= -CH_2CH_3$) at the SAM//Ga$_2$O$_3$ interface with a Lewis acid/base (e.g., T $= -CO_2H$), does not influence the tunneling current. Junctions of the same length ($d[Å]$ or $d[S(CH_2)_nT]$) and with composition Ag^{TS}/S$(CH_2)_n$T//Ga$_2$O$_3$, where T $= -CH_3$, $-OH$, $-SH$, $-CO_2H$, $-CONH_2$, and $-PO_3H$, all have tunneling currents that are indistinguishable (e.g., within a factor of 3). The introduction of protic polar groups at the T//Ga$_2$O$_3$ interface by the group T does not change the shape (i.e., the height or width relative to n-alkanethiolates) of the tunneling barrier enough to influence the rate of charge tunneling observably (a conclusion that is reinforced by data from studies of other organic groups, including a number of simple aromatics and uncharged polar groups).[4,5] The similarity
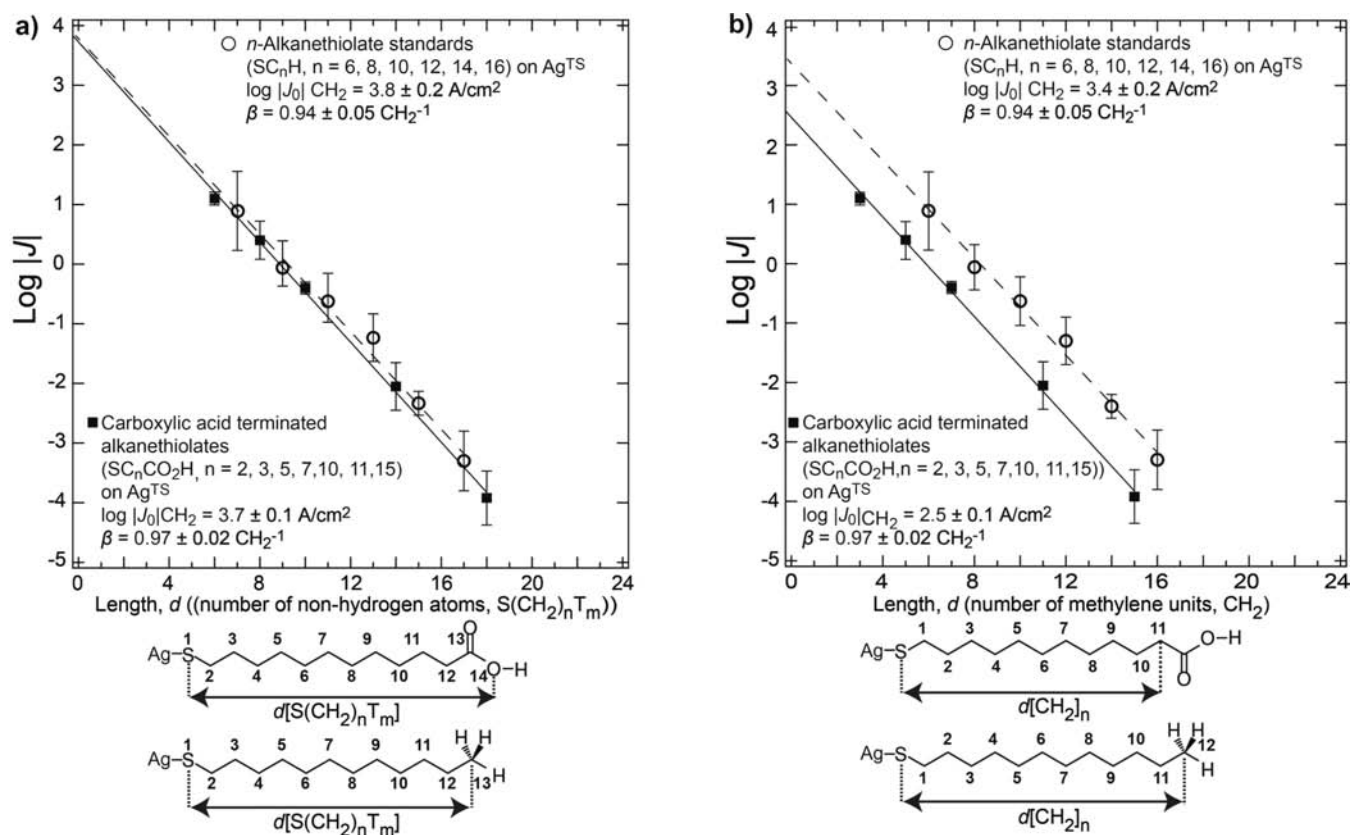
Figure 4. (a) Plot of the Gaussian mean values of log|*J*| at +0.5 V versus molecular length in number of non-hydrogen atoms (*n* + *m*: *n* is the number of non-hydrogen atoms of the polymethylene chain and *m* is the number of non-hydrogen atoms (in linear connection) of T; here, *n* is 11 and *m* is 2 for T = −CO₂H) for carboxyl-terminated alkanethiolates and n-alkanethiolate standards of similar length on Ag^TS. (b) Plot of the Gaussian mean values of log|*J*| at +0.5 V versus molecular length in number of methylene units (CH₂) for carboxyl-terminated alkanethiolates and n-alkanethiolate standards on Ag^TS. The final methylene unit of the terminal methyl group −(CH₂)H group is included in the total number of methylene units.

of the injection current (J_0) for junctions derived from data using SAMs terminated in $-CH_3$ or $-(CH_2)_nCH_3$ (depending on the size of the group to be compared) and for junctions from SAMs terminated in a variety of other functional groups (including simple aromatic groups,[5] polar aprotic groups with large dipole moments,[4] and the polar, protic groups studied here) indicates that these $T//Ga_2O_3$ interfaces are all very similar in their contribution to the tunneling barrier.

A comparison of J_0 for $T = -CO_2H$ and $T = -CH_2CH_3$ for similar extended lengths (Å) or number of non-hydrogen atoms is compatible with the hypothesis that both act primarily as (equivalent) contributors to the width of the tunneling barrier. Any difference in their contribution to the energetic topography of the tunneling barrier does not appear as differences in our experimental measurements. An analysis of conjugated compounds having a smaller HOMO−LUMO gap may reveal more interesting changes to the tunneling barrier, and will be the focus of a separate investigation.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The experimental procedures, characterization of the SAMs, histograms of $J(V)$ data, and DFT computational details. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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ABBREVIATIONS

EGaIn, eutectic gallium indium; SAM, self-assembled monolayer; TS, template-stripped; HOMO, highest occupied molecular orbital; LUMO, lowest unoccupied molecular orbital

REFERENCES

(1) Salomno, A.; Böcking, T.; Goding, J. J.; Cahen, D. *Nano Lett.* **2006**, *6*, 2873−2876.

(2) Liao, K.-C.; Yoon, H. J.; Bowers, C. M.; Simeone, F. C.; Whitesides, G. M. *Angew. Chem., Int. Ed.* **2014**, *53*, 3889−3893.

(3) Thuo, M. M.; Reus, W. F.; Simeone, F. C.; Kim, C.; Schulz, M. D.; Yoon, H. J.; Whitesides, G. M. *J. Am. Chem. Soc.* **2012**, *134*, 10876−10884.

(4) Yoon, H. J.; Bowers, C. M.; Baghbanzadeh, M.; Whitesides, G. M. *J. Am. Chem. Soc.* **2014**, *136*, 16−19.

(5) Yoon, H. J.; Shapiro, N. D.; Park, K. M.; Thuo, M. M.; Soh, S.; Whitesides, G. M. *Angew. Chem., Int. Ed.* **2012**, *51*, 4658−4661.

(6) Weiss, E. A.; Kaufman, G. K.; Kriebel, J. K.; Li, Z.; Schalek, R.; Whitesides, G. M. *Langmuir* **2007**, *23*, 9686−9694.

(7) Reus, W. F.; Thuo, M. M.; Shapiro, N. D.; Nijhuis, C. A.; Whitesides, G. M. *ACS Nano* **2012**, *6*, 4806−4822.

(8) Simeone, F. C.; Yoon, H. J.; Thuo, M. M.; Barber, J. R.; Smith, B.; Whitesides, G. M. *J. Am. Chem. Soc.* **2013**, *135*, 18131−18144.

(9) Thuo, M. M.; Reus, W. F.; Nijhuis, C. A.; Barber, J. R.; Kim, C.; Schulz, M. D.; Whitesides, G. M. *J. Am. Chem. Soc.* **2011**, *133*, 2962−2975.

(10) Nerngchamnong, N.; Yuan, L.; Qi, D. C.; Li, J.; Thompson, D.; Nijhuis, C. A. *Nat. Nanotechnol.* **2013**, *8*, 113−118.

(11) Nijhuis, C. A.; Reus, W. F.; Siegel, A. C.; Whitesides, G. M. *J. Am. Chem. Soc.* **2011**, *133*, 15397−15411.

(12) Nijhuis, C. A.; Reus, W. F.; Whitesides, G. M. *J. Am. Chem. Soc.* **2010**, *132*, 18386−18401.

(13) Nijhuis, C. A.; Reus, W. F.; Barber, J. R.; Dickey, M. D.; Whitesides, G. M. *Nano Lett.* **2010**, *10*, 3611−3619.

(14) Nijhuis, C. A.; Reus, W. F.; Whitesides, G. M. *J. Am. Chem. Soc.* **2009**, *131*, 17814−17827.

(15) Haj-Yahia, A. E.; Yaffe, O.; Bendikov, T.; Cohen, H.; Feldman, Y.; Vilan, A.; Cahen, D. *Adv. Mater.* **2013**, *25*, 702−706.

(16) Cui, X. D.; Primak, A.; Zarate, X.; Tomfohr, J.; Sankey, O. F.; Moore, A. L.; Moore, T. A.; Gust, D.; Harris, G.; Lindsay, S. M. *Science* **2001**, *294*, 571−574.

(17) Pujari, S. P.; van Andel, E.; Yaffe, O.; Cahen, D.; Weidner, T.; van Rijn, C. J.; Zuilhof, H. *Langmuir* **2013**, *29*, 570−580.

(18) Yan, H.; Bergren, A. J.; McCreery, R. L. *J. Am. Chem. Soc.* **2011**, *133*, 19168−19177.

(19) Sayed, S. Y.; Fereiro, J. A.; Yan, H. J.; McCreery, R. L.; Bergren, A. J. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109*, 11498−11503.

(20) Donhauser, Z. J.; Mantooth, B. A.; Kelly, K. F.; Bumm, L. A.; Monnell, J. D.; Stapleton, J. J.; Price, D. W., Jr; Rawlett, A. M.; Allara, D. L.; Tour, J. M.; Weiss, P. S. *Science* **2001**, *292*, 2303−2307.

(21) Simmons, J. G. *J. Appl. Phys.* **1963**, *34*, 1793−1803.

(22) Anslyn, E. V.; Dougherty, D. A. *Modern Physical Organic Chemistry*; University Science: Sausalito, CA, 2006; p xxviii, 1095.

(23) Nijhuis, C. A.; Reus, W. F.; Barber, J. R.; Whitesides, G. M. *J. Phys. Chem. C* **2012**, *116*, 14139−14150.

(24) Chiechi, R. C.; Weiss, E. A.; Dickey, M. D.; Whitesides, G. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 142−144.

(25) Fracasso, D.; Muglali, M. I.; Rohwerder, M.; Terfort, A.; Chiechi, R. C. *J. Phys. Chem. C* **2013**, *117*, 11367−11376.

(26) Wan, A.; Jiang, L.; Sangeeth, S.; Nijhuis, C. A. *Adv. Funct. Mater.* **2014**, DOI: 10.1002/adfm.201304237.

(27) Cademartiri, L.; Thuo, M. M.; Nijhuis, C. A.; Reus, W. F.; Tricard, S.; Barber, J. R.; Sodhi, R. N. S.; Brodersen, P.; Kim, C.; Chiechi, R. C.; Whitesides, G. M. *J. Phys. Chem. C* **2012**, *116*, 10848−10860.

(28) Engelkes, V. B.; Beebe, J. M.; Frisbie, C. D. *J. Am. Chem. Soc.* **2004**, *126*, 14287−14296.

(29) Dweydari, A. W.; Mee, C. H. B. *Phys. Status Solidi A* **1975**, *27*, 223−230.

(30) De Silva, C. M.; Pandey, B.; Li, F.; Ito, T. *Langmuir* **2013**, *29*, 4568−4573.

(31) Sun, L.; Crooks, R. M.; Ricco, A. J. *Langmuir* **1993**, *9*, 1775−1780.

(32) Yang, H. C.; Dermody, D. L.; Xu, C. J.; Ricco, A. J.; Crooks, R. M. *Langmuir* **1996**, *12*, 726−735.

(33) Reus, W. F.; Nijhuis, C. A.; Barber, J. R.; Thuo, M. M.; Tricard, S.; Whitesides, G. M. *J. Phys. Chem. C* **2012**, *116*, 6714−6733.

(34) Vilan, A.; Yaffe, O.; Biller, A.; Salomon, A.; Kahn, A.; Cahen, D. *Adv. Mater.* **2010**, *22*, 140−159.

(35) Yaffe, O.; Scheres, L.; Segev, L.; Biller, A.; Ron, I.; Salomon, E.; Giesbers, M.; Kahn, A.; Kronik, L.; Zuilhof, H.; Vilan, A.; Cahen, D. *J. Phys. Chem. C* **2010**, *114*, 10270−10279.

(36) Wang, W. Y.; Lee, T.; Reed, M. A. *Phys. Rev. B* **2003**, *68*, 035416.

(37) Wold, D. J.; Frisbie, C. D. *J. Am. Chem. Soc.* **2001**, *123*, 5549−5556.

(38) Cui, X. D.; Zarate, X.; Tomfohr, J.; Sankey, O. F.; Primak, A.; Moore, A. L.; Moore, T. A.; Gust, D.; Harris, G.; Lindsay, S. M. *Nanotechnology* **2002**, *13*, 5−14.

(39) Love, J. C.; Estroff, L. A.; Kriebel, J. K.; Nuzzo, R. G.; Whitesides, G. M. *Chem. Rev.* **2005**, *105*, 1103−1169.