



Odd–Even Effects in Charge Transport across n - Alkanethiolate-Based SAMs

Citation

Baghbanzadeh, Mostafa, Felice C. Simeone, Carleen M. Bowers, Kung-Ching Liao, Martin Thuo, Mahdi Baghbanzadeh, Michael S. Miller, Tricia Breen Carmichael, and George M. Whitesides. 2014. " Odd–Even Effects in Charge Transport Across n -Alkanethiolate-Based SAMs ." Journal of the American Chemical Society 136 [48] (December 3): 16919–16925. doi:10.1021/ja509436k.

Published Version

doi:10.1021/ja509436k

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:16654772>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Open Access Policy Articles, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP>

Share Your Story

The Harvard community has made this article openly available.
Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

Odd-Even Effects in Charge Transport across *n*-Alkanethiolate-Based SAMs

Mostafa Baghbanzadeh,^a Felice C. Simeone,^a Carleen M. Bowers,^a Kung-Ching Liao,^a Martin M. Thuo,^a Mahdi Baghbanzadeh,^b Michael Miller,^c Tricia Breen Carmichael,^c and George M. Whitesides^{a,d*}

^aDepartment of Chemistry and Chemical Biology, Harvard University,
12 Oxford Street, Cambridge, MA 02138, United States

^bDepartment of Statistics, Shiraz University, Shiraz, Iran

^cDepartment of Chemistry and Biochemistry, University of Windsor, 401 Sunset Avenue,
Windsor, Ontario, Canada, N9B 3P4

^dWyss Institute of Biologically Inspired Engineering, 60 Oxford Street, Cambridge, MA 02138,
United States

* *To whom correspondence may be addressed: gwhitesides@gmwgroup.harvard.edu*

ABSTRACT

This paper compares rates of charge transport across self-assembled monolayers (SAMs) of n -alkanethiolates having odd and even numbers of carbon atoms (n_{odd} and n_{even}) using junctions with the structure of $M^{TS}/SAM//Ga_2O_3/EGaIn$ ($M = Au$ or Ag). Measurements of current density, $J(V)$, across SAMs of n -alkanethiolates on Au^{TS} and Ag^{TS} demonstrated a statistically significant odd-even effect on Au^{TS} , but not on Ag^{TS} (that could be detected using this technique). Statistical analysis showed the values of tunneling current density across SAMs of n -alkanethiolates on Au^{TS} with n_{odd} and n_{even} belong to two separate data sets, and while there is a significant difference between the values of injection current density, J_0 , for these two series ($\log|J_{0Au,even}| = 4.0 \pm 0.3$ and $\log|J_{0Au,odd}| = 4.5 \pm 0.3$), the values of tunneling decay constant, β , for n_{odd} and n_{even} alkyl chains are indistinguishable ($\beta_{Au,even} = 0.73 \pm 0.02 \text{ \AA}^{-1}$, and $\beta_{Au,odd} = 0.74 \pm 0.02 \text{ \AA}^{-1}$). A comparison of electrical characteristics across junctions of n -alkanethiolate SAMs on gold and silver electrodes yields indistinguishable values of β and J_0 and indicates that a change that substantially alters the tilt angle of the alkyl chain (and, therefore, the thickness of the SAM) has no influence on the injection current density across SAMs of n -alkanethiolates.

Keywords: Odd-even effect; tunneling; interface; self-assembled monolayer; EGaIn

INTRODUCTION

Understanding charge tunneling through thin molecular films is a current focus of nanoscience.¹⁻⁷ Using self-assembled monolayer (SAM)-based large-area junctions with the structure $\text{Ag}^{\text{TS}}/\text{S}(\text{CH}_2)_n\text{T}/\text{Ga}_2\text{O}_3/\text{EGaIn}$ (one type of so-called “EGaIn junction”),^{8,9} we were able to study the influence of the changes in the structure of the SAM on the tunneling current density.¹⁰⁻¹⁴ (Here Ag^{TS} is a template-stripped silver substrate; $\text{S}(\text{CH}_2)_n$ is the n -alkanethiolate SAM covalently bonded to the Ag^{TS} substrate, T is the terminal functional group; and EGaIn is the liquid alloy of gallium and indium, covered with a thin, electrically conductive surface oxide—mostly Ga_2O_3 —that forms spontaneously upon exposure to air.^{15,16}) Those studies showed that alterations in the structure of the insulating organic layer, $\text{S}(\text{CH}_2)_n\text{T}$,—for example, changing the anchoring group of the SAMs¹⁰ or introducing polar organic groups either into the backbone of a polyethylene chain¹¹ or at the van der Waals $\text{T}/\text{Ga}_2\text{O}_3$ interface¹²⁻¹⁴—do not influence the rates of charge transport at a level that is statistically significant (less than a factor of three). In surprising contrast, we and others observed that the addition of one CH_2 group to the alkyl chain—a change that, in essence, simply interchanges an exposed terminal methyl group for an ethyl group—appears to be sufficient to make a small but statistically significant difference in the electronic properties of the junction.¹⁷⁻²⁰ This phenomenon is one manifestation of the so-called odd-even effect,²¹ and its origin is a continuing puzzle in understanding SAM-based tunneling junctions.

In this work, we focused on these specific questions about the odd-even effect: i) Is there indeed—when examined using current technology—a systemic difference in the rate of charge transport across SAMs of n -alkanethiolates (SC_n) with an odd number of carbons (n_{odd}) and SAMs with an even number of carbons (n_{even})? (Much of the historical evidence for odd-even

effects in charge transport has come from earlier and less accurate studies,¹⁷ and from studies of phenomena such as wetting, which are of unknown relevance to quantum tunneling.²¹) ii) If there is an odd-even effect, then, mechanistically, how can such a small change in the structure of a SAM influence tunneling probabilities? iii) How does changing the substrate for the SAM from Au to Ag—a change that also changes the tilt angle of *n*-alkanethiolates as well as properties, such as wetting and work function of electrode—influence tunneling current density across SAM-based large-area junctions?

There are three plausible explanations for the observed odd-even effect in the rates of charge transport: i) Changes in the nature of the van der Waals interface between the SAM and the top electrode—changes that are presumed to be responsible for the odd-even effect in wetting²¹—might also influence the ability of the SAM and the Ga₂O₃ to “wet” and conform to one another, or to condense a water film, or to adsorb adventitious contaminants at the interface. ii) Differences in rates of charge transport might reflect the differences in the orientation of the terminal group at the interface of the SAM with the Ga₂O₃ (e.g., CH₂CH₃ vs. CH₃, Figure S2), which might influence the strength of electronic coupling between the HOMOs of the *n*-alkyl groups and the Ga₂O₃. iii) There might be a systematic difference in the thickness of the SAM between odd and even *n*-alkanethiolates. (The tunneling path might have a through-space component and thus be sensitive to the thickness, independently of the length of the *n*-alkyl chain.) A fourth (in principle) possibility—difference in the electric dipole moment along the surface normal, which would be induced by the odd-even differences in the orientation of the terminal ethyl (–CH₂CH₃) group—seems unlikely to be important since the difference is undoubtedly small, and introducing even large dipoles into the interface has little or no effect.^{12,13}

In our previous studies, although we were able to identify an odd-even effect in tunneling current density, J (A/cm²) at ± 0.5 V, (i.e., the results from SAMs with n_{even} and n_{odd} belonged to separate data sets and demanded separate fits to eq. 1) we were not able—because the log-standard deviation (σ_{\log}) in those studies was large ($\sigma_{\log} = 0.6$ - 1.4) relative to those we now generate ($\sigma_{\log} = 0.3$ - 0.6)—to determine the mechanism of the odd-even effect, or to establish whether there was a statistically significant difference in the two parameters, β , and, J_0 , of the simplified Simmons equation (eq. 1).¹⁷ In Eq. 1, $J(V)$ is current density (current divided by the geometrical contact area; A/cm²) at an applied voltage V .^{22,23}

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

In this study, as in prior work, we have focused on trends in current densities as a function of the number of methylene (-CH₂-) units in SAMs of structure M(Au or Ag)/SC_n//Ga₂O₃/EGaIn, rather than on absolute values of these measurements. We have described details of the procedure we used previously.¹⁵ Here we used so-called “flattened” EGaIn tips, $V = \pm 0.5$ V and template-stripped (TS) Ag and Au substrates (Figure 1).^{8,9,15} (Our experiments, however, showed that the J value is independent of the type of the tip—selected¹⁴ or flattened¹⁵—but using flattened tips yields in data with slightly narrower distribution). These modifications in procedure generate data with smaller standard deviations, and over larger range of data, than those data generated using unflattened/unselected tips.

Surface of Au and Ag have similar work functions ($\Phi_{Au} = 4.9$ eV and $\Phi_{Ag} = 4.4$ eV).²⁴ The tilt angle of the backbone from the surface normal for n -alkanethiolate monolayers on Au(111) ($\sim 30^\circ$) is larger than that on Ag(111) ($\sim 10^\circ$) (Figure S2).²⁵ Accordingly, comparing the

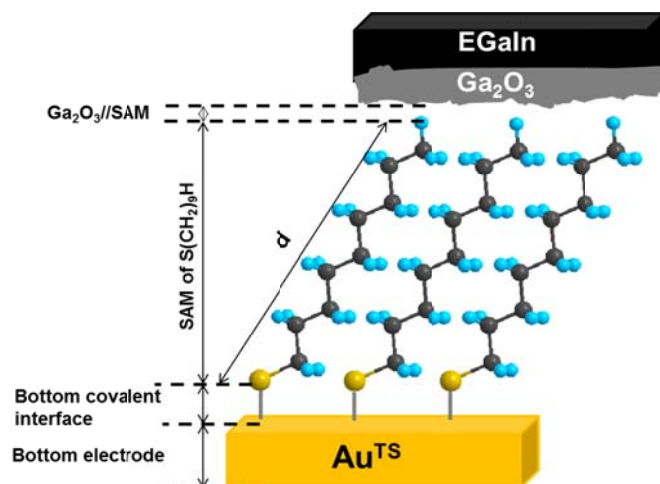


Figure 1. Schematic structure of a $\text{Au}^{\text{TS}}/\text{SAM}//\text{Ga}_2\text{O}_3/\text{EGaIn}$ junction. Here, d represents the length of the tunneling barrier established by the alkyl chains in the SAM. Assuming a through-bond mechanism, d coincides with the length of the alkyl chain. J_0 is defined as the current density across a hypothetical junction where $d = 0$.

rate of charge transport across the *n*-alkanethiolate SAMs on Au and Ag substrates makes it possible to distinguish several characteristics of a SAM, such as the tilt angle (and thus the relative thickness of the SAM along the surface normal) and the SAM packing density (21.7 Å²/molecule on Au and 19.1 Å²/molecule on Ag).²⁶ In particular, we hoped to answer two questions in this comparative study: i) Does the charge move along the shortest distance between the two electrodes (a through-space path)? or ii) does the charge follow the molecular orbitals along the backbone regardless of the tilt of the *n*-alkyl group (a through-bond path)?^{27,28} Density of chains, tilt angle, and the properties of the interface (T//Ga₂O₃, T = —CH₃, —CH₂CH₃) are obviously convoluted, and no simple comparison of SAMs on Au and Ag will distinguish them all unambiguously; our results do, nonetheless, both allow some possibilities to be excluded, and help to frame questions for future study.

We observed a statistically significant odd-even effect in the rates of tunneling across SAMs of *n*-alkanethiolate on Au^{TS}, where *n*-alkanethiolates with *n*_{odd} gave higher current densities (*J*(*V*)) than did SAMs of *n*-alkanethiolate with *n*_{even}. We show that the tunneling current densities across SAMs of *n*-alkanethiolates with *n*_{odd} and *n*_{even} on Au^{TS} substrate fit in separate data sets, when analyzed using the simplified Simmons model (eq. 1); that is, analyzing the two series separately led to more consistent interpretations of the results than analyzing them together. In contrast, we notice that charge tunneling across SAMs of *n*-alkanethiolate on Ag^{TS} does not show an odd-even effect that we can detect in either β or J_0 .

Background

Odd/Even effects in tunneling across SAMs. The odd-even effect in SAMs has been observed (and reviewed²¹) in a number of different physical properties, such as wetting by liquids,²⁹⁻³² molecular packing,³³ and electronic,¹⁹ frictional,³⁴ and electrochemical properties.³⁵

Odd-even effects have been studied in the surface treatment of dielectric materials for pentacene-based field-effect transistors,³⁶ and in the rate of charge transport across carbon-chain-based molecular devices.²⁰ Odd-even alternation in rectification of tunneling current density has also been reported.¹⁸ Using EGaIn-based top electrodes in molecular junctions, we have studied odd-even effects in charge transport across *n*-alkanethiolate SAMs on Ag^{TS} substrates.^{17,11} Using statistical tools, we showed that the data for current densities for SAMs with n_{even} and n_{odd} belong to separate data sets.³⁷

Theory of charge tunneling across SAMs. SAMs of alkanes are considered to be good electrical insulators for current transport at low bias (we use ± 0.5 V), and charge transport takes place by hole tunneling.^{38,39} When such molecules are placed between two electrodes, the charge transport has usually been interpreted (in the absence of a more detailed model) in terms of a rectangular barrier model using the Eq. 1.²² The injection current density at an applied voltage V , $J_0(V)$, gives, ideally, the current flowing across a hypothetical junction in which the SAM has zero ($d = 0$) thickness, but the characteristic of the interfaces between the SAM and the electrodes remain the same as those when there is a SAM. The tunneling decay constant β (\AA^{-1}) contains, according to the Simmons model, information about the shape of the tunneling barrier, which, in principle, is determined by the molecular/electronic structure of the backbone in the SAM. The width of the barrier across which charges traverse is d (\AA), and is usually assumed to be determined by the molecular structure, not the shortest path between the two electrodes, but this assumption is not based either on solid empirical or theoretical grounds.

RESULTS AND DISCUSSION

We collected $J(V)$ using “flattened” conical tips. The procedures for formation and use of these flattened tips are described in detail elsewhere.¹⁵ (See the Supporting Information for details of experimental design.)

Charge transport across n -alkanethiolates on Ag^{TS} and Au^{TS} substrates. Values of J are approximately log-normally distributed. For each SAM, we could fit, by nonlinear least-squares fitting,³⁷ Gaussian curves to the distributions of $\log|J|$. Figure S3 (in Supporting Information) shows the histograms for the values of $\log|J|$ (J , Acm⁻²) for SAMs of n -alkanethiolates on Ag^{TS}. Figure S4 shows analogous data for SAMs formed on Au^{TS} substrates. Table S1 summarizes the values of $\log|J|$ at $V = +0.5$ V for SAMs of n -alkanethiolates (SC _{n}) on Ag^{TS} and Au^{TS} with both odd and/or even number of carbons (n_{odd} and n_{even}). Table 1 summarizes the values for injection current density, $\log|J_0|$, and tunneling decay coefficient, β , for the n -alkanethiolates with n_{even} and n_{odd} on both Ag and Au substrates. Figure 2 shows plots of linear regression of $\log|J|$ versus molecular length (number of carbons) for SAMs of n -alkanethiolate on Ag (Figure 2a) and Au (Figure 2b) with n_{even} and n_{odd} . Figure S5 shows plots of $\log|J|$, at $V = +0.5$ V, versus $d(\text{\AA})$ for different lengths of n -alkanethiolates on both Ag^{TS} and Au^{TS} substrates. We calculated the molecular length from the sulfur atom to the distal hydrogen atom of the final methyl group in contact with Ga₂O₃ (Figure 1).

For SAMs on Au^{TS}, junctions comprising SAMs of n -alkanethiolates with n_{odd} consistently showed higher values of current densities than their analogs with n_{even} (Figures 2b and 3). Based on a careful statistical analysis, we concluded, with 95% probability, that there is a significant difference between two regression lines (Figure 2b). We determined that the

Table 1. Values for injection current density, $\log|J_0|$, and tunneling decay coefficient, β , for the n -alkanethiolates with n_{even} and n_{odd} on both Ag^{TS} and Au^{TS} substrate.

M^a/odd or even	Length (Å)^b		Length (n_C)^c	
	$\log J_0 $	β (Å ⁻¹)	$\log J_0 $	β (n _C ⁻¹)
$\text{Ag}^{\text{TS}}/\text{even}$	3.7±0.3	0.73±0.02	3.4±0.3	0.93±0.02
$\text{Ag}^{\text{TS}}/\text{odd}$	3.6±0.3	0.71±0.02	3.3±0.3	0.91±0.02
$\text{Au}^{\text{TS}}/\text{even}$	4.0±0.3	0.73±0.02	3.6±0.3	0.93±0.02
$\text{Au}^{\text{TS}}/\text{odd}$	4.5±0.3	0.74±0.02	4.1±0.3	0.94±0.02

^aThe metal substrate. ^bMolecular length from the sulfur atom to the distal hydrogen atom of the final methyl group in contact with Ga_2O_3 (Figure 1). ^cLength based on the number of carbons of SC_n .

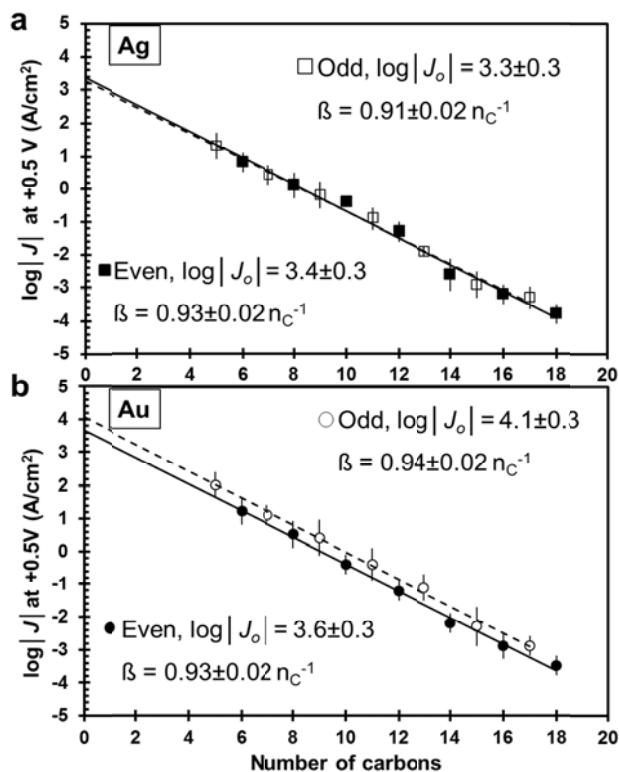


Figure 2. $\log|J|$ at $V = +0.5\text{V}$ versus number of carbons for SAMs of n -alkanethiolates (SC_n) on a) Ag^{TS} and b) Au^{TS} . Solid line (for n -alkanethiolate SAMs with n_{even}) and dashed line (for n -alkanethiolate SAMs with n_{odd}) represent the linear regression analyses which gives $\beta/2.303$ (slopes) and $\log|J_0|$ (intercepts at $d = 0$). Error bars represent the standard deviation for the $\log|J|$ values ($0.1 \geq \sigma_{\log} \geq 0.6$).

difference in the values of the intercepts ($\log|J_0|$) of the two lines is statistically significant, but the slopes (β) are indistinguishable (for details of statistical analysis; see Supporting Information). We did not, however, observe any significant difference in the trends of $\log|J|$ (i.e., an odd-even alternation) for SAMs of *n*-alkanethiolates with n_{even} or n_{odd} on Ag^{TS} (Figure 2a). Statistical analysis, similar to what we have done for SAMs on Au^{TS} , for SAMs of *n*-alkanethiolates with n_{even} or n_{odd} on Ag^{TS} showed that the two lines are indistinguishable and values of the injection current density, $\log|J_0|$, and of tunneling decay coefficient, β , for the *n*-alkanethiolates with n_{even} were indistinguishable from $\log|J_0|$, and β for *n*-alkanethiolates with n_{odd} .

For SAMs on Au^{TS} , values of $\log|J|$ of most of the *n*-alkanethiolate SAMs with n_{even} (SC_n) were within 0.1 of the values of $\log|J|$ of their next homolog with n_{odd} (SC_{n+1}) (Figure 3a). Figure 3b shows that the $\Delta\log|J|$ ($\Delta\log|J| = \log|J_{\text{observed}}| - \log|J_{\text{fitted}}|$) for SAMs with n_{odd} are constantly ≤ 0 while $\Delta\log|J|$ for SAMs with n_{even} are constantly ≥ 0 .

To examine the statistical difference between the tunneling current density values, $\log|J|$, of SAMs of *n*-alkanethiolates on Au^{TS} we calculated the 95% confidence intervals (CI) for the whole set of $\log|J|$ values (for details see SI). Error bars in Figure 3 show the 95% CI for the $\log|J|$ values on Au^{TS} substrate (i.e., the smaller the overlap of bars, or the larger the gap between bars, the stronger the evidence for a true difference).⁴⁰ Figure 3b shows an interesting phenomenon; that is, although the odd-even effect alternation can be observed for the whole series of SC_n ($n = 5-18$), it is only statistically significant for $10 \leq n \leq 14$. We rationalize this difference as a reflection of the conclusion—drawn largely from spectroscopic studies⁴¹—that SAMs with longer SAMs ($n \geq 10$) are crystalline and well ordered, while those with $9 \geq n$ are disordered, probably because of weak interactions between the shorter alkyl chains. The SAMs

with long chain— $n \geq 15$ —may be less ordered and have chains with gauche configurations (similar observations have been reported for some other types of odd-even effect^{18,42}). Our data are consistent with suggestions that the magnitude of odd-even effect depends on the degree of order of the SAM.

One of the factors that, potentially, can influence the quality of the SAM is the incubation time (i.e., the time that metal substrate stayed in a solution of the thiols (1 mM in toluene)). To examine the effect of incubation time, we prepared SAMs of SC₁₀ and SC₁₁ on both Ag^{TS} and Au^{TS} substrates with incubations of 3 h, 1 day, 2 day, and 7 day. The rate of charge tunneling for SAMs formed over 3 h is not distinguishable from the 7 day sample (Table S2).

Comparison between Au and Ag. To examine the influence of geometry of SAMs on tunneling transport, we compared $J(V)$ of n -alkanethiolates on Au^{TS} and Ag^{TS}. Figure 4 shows plots of $\log|J|$ at $V = +0.5$ versus molecular length (in number of carbons) for n -alkanethiolate SAMs with n_{even} and n_{odd} on both Au^{TS} and Ag^{TS}. Statistical analysis, similar to that which we have carried out for the odd-even effect, showed that SAMs with n_{even} on both Au^{TS} and Ag^{TS} result in indistinguishable values of $\log|J_0|$ and β (Table 1, Figure 4a). When, however, we compared the tunneling current density between SAMs with n_{odd} on Ag^{TS} and Au^{TS}, we observed a significant difference in values of $\log|J_0|$, while the values of β were indistinguishable (Table 1, Figure 4b). These comparisons lead to two important conclusions:

i) They indicate that replacing Au/SR with Ag/SR (for SAMs with n_{even})—a change that substantially alters the tilt angle of the alkyl chain (and, therefore, the thickness of the SAM)²⁹—had no influence (to the precision that we can measure) on the injection current density across these SAMs (Figure 4a).

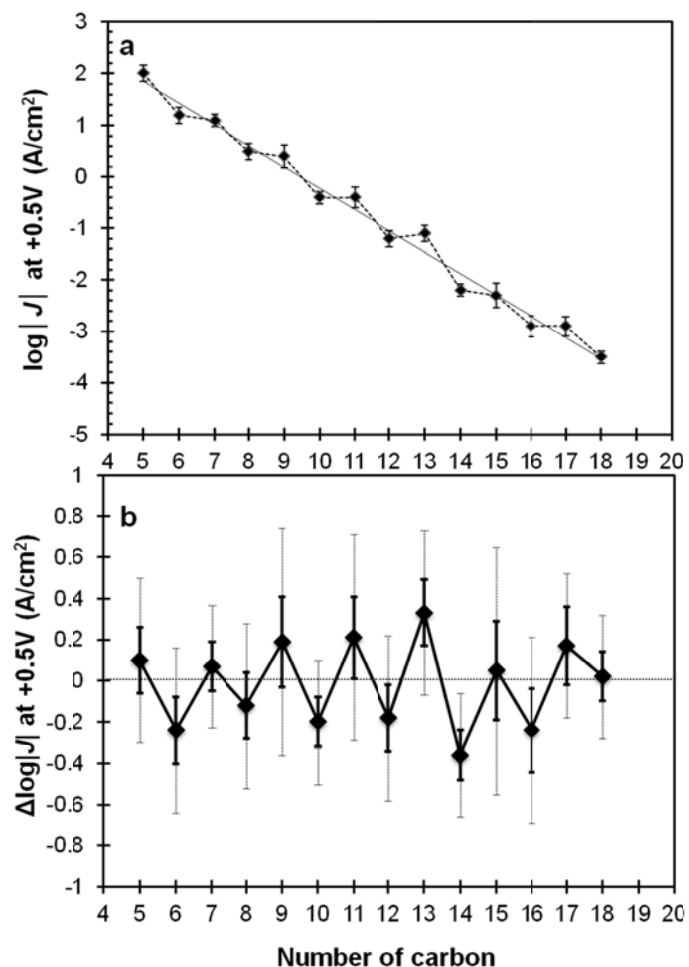


Figure 3. Odd-even effect in charge transport across *n*-alkanethiolates on Au^{TS}. a) Plot of $\log|J|$ at $V = +0.5V$ versus number of carbons for SAMs of *n*-alkanethiolates on Au^{TS} (SC_{*n*}, *n*=5-18). The solid line represents the linear regression analysis to *all* the data. Error bars represent 95% CI for the $\log|J|$ values. b) Difference ($\Delta\log|J|$) between the observed current density ($\log|J_{\text{observed}}|$) and the calculated current density ($\log|J_{\text{fitted}}|$) based on the regression line ($\Delta\log|J| = \log|J_{\text{observed}}| - \log|J_{\text{fitted}}|$). Error bars represent standard deviation (dashed) and 95% CI (solid) for the $\log|J|$ values.

ii) The odd-even effect in charge tunneling across the SAMs of n -alkanethiolates *is* related to the orientation of the terminal methyl group. This study showed that SAMs of n -alkanethiolates with n_{even} on Au^{TS} behave, in EGaIn junctions, similarly to the SAMs with n_{even} and n_{odd} on Ag^{TS}, and that only SAMs with n_{odd} on Au^{TS} conduct differently (Figure 4 and Table 1). The significant structural difference between SAMs with n_{odd} on Au^{TS} with the other SAMs studied in this comparison is the orientation of terminal ethyl group: for SAMs with n_{even} on Au^{TS}, and SAMs with n_{even} and n_{odd} on Ag^{TS}, the surface consists predominantly of methyl groups. The terminal CH₂-CH₃ moiety of the SAMs with n_{odd} on Au^{TS} is tilted away from the surface normal, producing a surface that is composed of a mixture of methyl and methylene groups (that is, an “ethyl” rather than “methyl” surface) (Figure S2). The same behavior was reported in wetting properties of SAMs on Ag and Au; SAMs of n -alkanethiolate on Ag showed no²⁹ or slight⁴² odd-even effect; the effect was more distinguishable on Au.⁴³

CONCLUSION

The odd-even effect in charge transport by tunneling is real. Our statistical analysis for SAMs of n -alkanethiolates on Au^{TS} showed i) the values of tunneling current density across SAMs of n -alkanethiolates with n_{odd} and n_{even} belong to two separate data sets, and ii) while there is a significant difference between the values of J_0 for these two series, the values of β for n_{odd} and n_{even} alkyl chains were indistinguishable. We conclude that there is an odd-even effect in tunneling transport across SAMs on Au^{TS}; an odd-even effect, however, was *not* observable (at the precision that we could measure) for the series on Ag^{TS}.

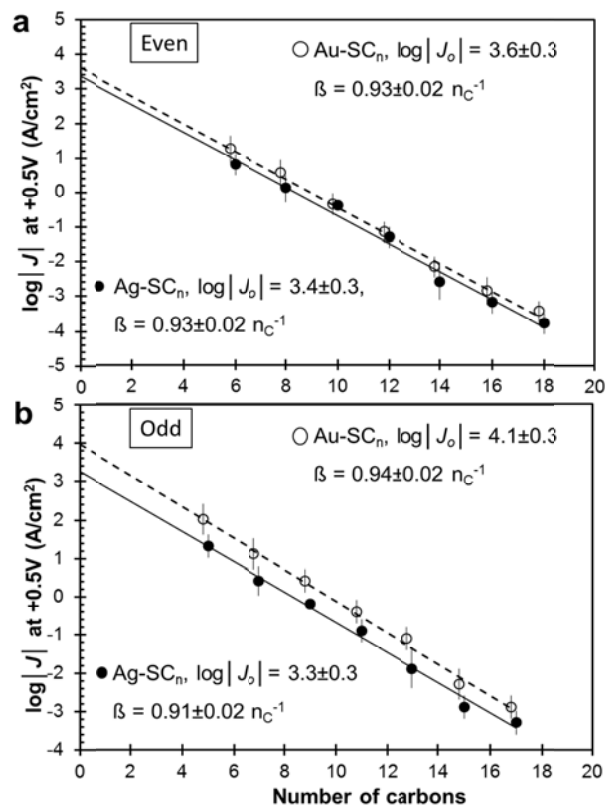


Figure 4. $\log|J|$ at $V = +0.5V$ versus number of carbons for SAMs of n -alkanethiolates a) with an even number of carbons on Au^{TS} and Ag^{TS} and b) with an odd number of carbons on Au^{TS} and Ag^{TS}. Solid line (for n -alkanethiolate SAMs on Ag^{TS}) and dashed line (for n -alkanethiolate SAMs Au^{TS}) represent the linear regression analyses which give $\beta/2.303$ (slopes) and $\log|J_0|$ (intercepts at $d = 0$). Error bars represent the standard deviation for the $\log|J|$ values.

The geometry of the n -alkyl chain determines the odd-even effect. The contrast of junction measurements between SAMs of n -alkanethiolates on gold (where we observed an odd-even effect) and on silver (where we did not observe a significant trend) indicates that the odd-even effect in tunneling transport corresponds to the composition (“methyl” vs. “ethyl”) of the surface of the SAM (Figure S2).

The tunneling path is “along single molecule” rather than “across multiple molecules”. Our results demonstrate that although a SAM on gold is thinner than one on silver, the values of J_0 and β for SAMs of n -alkanethiolates with n_{even} on Au^{TS} and Ag^{TS} are statistically indistinguishable (Figure 4a). We suggest—based on this observation—that charge carriers travel through the backbone of the alkyl chain in the SAM, rather than across the shortest (and thus across multiple molecules of n -alkanethiolate) distance between the two electrodes.

The SAM//Ga₂O₃ interface is responsible for the odd-even effect on Au^{TS}. Significant differences in values of injection current densities, J_0 , and indistinguishable values of tunneling decay, β , for SAMs of n -alkanethiolates with n_{odd} and n_{even} imply that the odd-even effect is influenced by some property of the interfaces (e.g., Au/S or SAM//Ga₂O₃). We suggest that a determining contribution of the SAM//Ga₂O₃ interface to odd-even effects is more plausible than one for the Au/S interface for two reasons: i) Our previous studies,^{10,44} and current study (Figure 4a), showed that changing the bottom interface does not significantly influence the tunneling current densities. ii) Results of this study indicate that changing the terminal group from CH₃ to CH₂CH₃ correlates with a change in the injection current density (Figures 2b and 4b).

The origin of the odd-even effect is not completely defined by currently available data. While we were able to identify the odd-even effect with respect to J , β , and J_0 , between n -alkanethiols with n_{odd} and n_{even} , we cannot pinpoint the origin of the observed odd-even effect on

Au^{TS}. We can, however, identify and assess four possibilities (although—based on our current and previous studies—some possibilities are less plausible than others).

(i) *Differences in the Orientation of the Terminal (T) Group at the Ga₂O₃ Interface (e.g., CH₂CH₃ vs. CH₃).* A larger exposure of terminal CH₂CH₃ group at the surface of the *n*-alkanethiolate SAMs with *n_{odd}* results in larger van der Waals interactions (by changing the polarizability of surface and increasing the area of contact) between the monolayer and the EGaIn tip, and may consequently give rise to a difference in *J(V)* (similar to wetting properties of SAMs on Au²¹). If the orientation of terminal CH₂–CH₃ bond is responsible for both the odd-even effect in charge transport, and the odd-even effect in wetting, then increasing the van der Waals interactions as a result of different surface polarization is a possible origin of the former. This hypothesis—that the odd-even effect in charge tunneling across SAMs terminating in ethyl and methyl groups reflects polarizability and van der Waals interactions—is not immediately easily reconciled with the fact that introducing groups such as halogens or aromatics into this interface does *not* produce large differences in *J₀* in our experiments.^{12,13} (Cahen and others have reported larger differences with specific terminal halogen substituents when using a mercury top electrode.⁴⁵)

(ii) *Systematic Alternations in Energy of the Frontier Orbital Energies (i.e. HOMO/LUMO levels) of Odd and Even n-Alkanethiolates.* Difference in rates of charge transport might reflect the difference in the orientation of the terminal group at the SAM interface between the Ga₂O₃ (CH₂CH₃ vs. CH₃, Figure S2) which might influence the strength of electronic coupling between the HOMOs of the *n*-alkyl groups and the Ga₂O₃. The HOMO in these SAMs is, however, concentrated at the Au-S interface, with little amplitude at the SAM/Ga₂O₃ interface.⁴⁶

(iii) *Systematic Differences in the Thickness of the SAM between Odd and Even n -Alkanethiolates.* Naively, it seemed that SAMs on gold with n_{odd} might be thinner than SAMs with n_{even} . Our calculation of thicknesses of odd and even SAMs suggests that there is no significant (<0.5 Å) systematic alternation in the thickness between n_{odd} and n_{even} . Figure S6b (in the SI) shows an essentially monotonic increase in the thickness for n -alkanethiolate monolayers with a tilt angle of 30° on Au^{TS}. These calculations indicate that there is no significant alternation in the thicknesses of the SAMs and thus that thickness does not correlate with the odd-even alternation in $J(V)$ (Figure S7). In addition, by comparing the rate of tunneling across SAMs of n -alkanethiolates on Au and Ag, we have shown empirically that charge transport is insensitive to the thickness of the SAMs (as measured along the perpendicular to the mean plane of the surface of the metal.). We conclude that there is no evidence to support a contribution of the thickness of the SAM to the presence of odd-even effect.

(iv) *Difference in the Dipole along the Surface Normal, which might Correlate with Odd-Even Differences in the Orientation of the Terminal CH₃ Group (Figure S2).* Different orientations of the terminal methyl group in n_{odd} and n_{even} could cause an odd-even alternation in the dipole along the surface normal,⁴⁷ which might contribute to an odd-even effect through an influence on the work function of the surface.^{19,47} Although we have no direct evidence to prove or exclude this hypothesis, our previous studies^{12,13} showed that introducing even a with a large dipole moment at the SAM//Ga₂O₃ interface does not change the tunneling barrier enough to influence the rate of charge transport; thus, we think this very small difference in dipole along surface normal seems unlikely to be important. To be proved or excluded, this hypothesis, however, needs more investigation (e.g., using a *series* of odd and even SAMs having terminal

polar groups such as CF₃ or OCH₃ that introduce a dipole at the interface but do not change the topography of the SAM).

If there is an observable odd/even effect for *n*-alkanes, why was there no detectable difference in much larger changes in terminal groups for SAMs? This paper confirms that there is an odd/even effect for *n*-alkanethiolates, but that it is small (a factor of ~3 when appropriately compared, or $\Delta \log J_0 \sim 0.5$), and only reliably detectable given the availability of a substantial number of structurally related compounds, with measurements taken carefully, and in parallel. Previous papers have shown that a range of groups with quite different polarities, degrees of saturation, composition, and polarizability have a surprisingly small influence on tunneling current densities.¹³ These two sets of observations seem at odds.

The problem in comparing these data is that they are not, strictly speaking, comparable. Most of our studies of terminal groups *did* show variability, but the variation (which might have been a factor of 10 across of series of groups) was not designed to detect differences as small as those characterizing the odd-even effect, and would require comparing groups known to have different sizes and shapes. In those studies, we compared the current densities of compounds having polar terminal groups (R) with those of hypothetical *n*-alkanethiolates of the same length. If those comparisons demonstrate that the difference in $\log|J|$ ($\Delta \log|J| = \log|J_{\text{polar}}| - \log|J_{\text{CH}_3}|$) was ≤ 0.5 , or less than a factor of three in $|J|$, we considered the compound with polar terminal group and *n*-alkanethiol to be indistinguishable. In the current study, however, we did not compare two single data points, but studied a series of compounds (S(CH₂)_nH, n = 5-18) and analyzed the results based on eq. 1. Although the $\Delta \log|J|$ for each adjacent pair of *n*-alkanethiolate was ≤ 0.4 (Figure 3b), analyzing the two series separately led to more consistent

interpretations of the results than did analyzing them together (n_{even} and n_{odd} produce two statistically distinguishable sets of data).

The surprise in these studies was thus that substituting, for example, a terminal methyl group for an amide, or a terminal cyclohexyl group with a phenyl, produced a change in current density ($J(V)$) of approximately a factor of 4.0 ($\Delta\log|J(0.5V)| = 0.6$),¹² and that was smaller than we had—perhaps naively— expected, while substituting a terminal methyl for a terminal ethyl produced a change of a factor of 2.5 ($\Delta\log|J(0.5V)| = 0.4$), which was larger than we had expected. The precision of the former studies was, however, substantially less than the latter, and the studies of polar and aromatic groups, as they were designed, would not have been able to detect the subtle differences characterizing the odd/even effect. Differences in size, composition, and other factors restricted our ability to make meaningful comparisons of current densities with $\Delta\log|J(0.5V)| \leq 0.6$.

So, what is the origin of the odd/even effect? Although this paper cannot answer the question unambiguously, it has eliminated a number of possibilities (differences in the thickness of the SAM, certain differences in the HOMOs for the SAMs), and leaves a focus on the contribution of the non-covalent interface between the SAM and the Ga₂O₃ film on the EGaIn electrode. This interface has been characterized empirically by studies such as those described in this paper, but have not yet been included in relevant theoretical calculations. In particular, the height of the barrier to tunneling is probably high in the region where there is only physical contact (relative to the rest of the SAM), but the width of this region is small. Understanding the mechanism of charge transport across this interface, and its contribution to overall tunneling currents, remains an unresolved problem with this junction (and, in fact, with all junctions involving SAMs as insulating layers between two conducting electrodes).

ASSOCIATED CONTENT

Supporting Information. The experimental procedures, synthesis characterization of the alkanethiols, histograms of $J(V)$ data, and statistical analysis details. This material is available free of charge via the Internet at <http://pubs.acs.org>.

AUTHOR INFORMATIONS

Corresponding Author

*E-mail: gwhitesides@gmwgroup.harvard.edu

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The work at Harvard University was supported by a subcontract from Northwestern University from the United States Department of Energy (DOE, DE-SC0000989). The DOE grant from Northwestern also supported the salary for M.B., C.M.B, and K.-C.L. Aspects of this work (SAM preparation and characterization) was supported by the US Department of Energy, Division of Materials Sciences, under Award No. DE-FG02-00ER45852.

REFERENCES

- (1) Bergfield, J. P.; Ratner, M. A. *Phys. Status Solidi B* **2013**, *250*, 2249.
- (2) McCreery, R. L.; Bergren, A. J. *Adv. Mater.* **2009**, *21*, 4303.
- (3) Salomon, A.; Cahen, D.; Lindsay, S.; Tomfohr, J.; Engelkes, V. B.; Frisbie, C. D. *Adv. Mater.* **2003**, *15*, 1881.
- (4) Wang, W. Y.; Lee, T.; Reed, M. A. *Rep. Prog. Phys.* **2005**, *68*, 523.
- (5) Vilan, A.; Yaffe, O.; Biller, A.; Salomon, A.; Kahn, A.; Cahen, D. *Adv. Mater.* **2010**, *22*, 140.
- (6) McCreery, R. L. *Chem. Mater.* **2004**, *16*, 4477.

- (7) Coskun, A.; Spruell, J. M.; Barin, G.; Dichtel, W. R.; Flood, A. H.; Botros, Y. Y.; Stoddart, J. F. *Chem. Soc. Rev.* **2012**, *41*, 4827.
- (8) Chiechi, R. C.; Weiss, E. A.; Dickey, M. D.; Whitesides, G. M. *Angew. Chem. Int. Ed.* **2008**, *47*, 142.
- (9) Dickey, M. D.; Chiechi, R. C.; Larsen, R. J.; Weiss, E. A.; Weitz, D. A.; Whitesides, G. M. *Adv. Funct. Mater.* **2008**, *18*, 1097.
- (10) Liao, K.-C.; Yoon, H. J.; Bowers, C. M.; Simeone, F. C.; Whitesides, G. M. *Angew. Chem. Int. Ed.* **2014**, *53*, 3889.
- (11) 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.
- (12) Yoon, H. J.; Shapiro, N. D.; Park, K. M.; Thuo, M. M.; Soh, S.; Whitesides, G. M. *Angew. Chem. Int. Ed.* **2012**, *51*, 4658.
- (13) Yoon, H. J.; Bowers, C. M.; Baghbanzadeh, M.; Whitesides, G. M. *J. Am. Chem. Soc.* **2014**, *136*, 16.
- (14) Bowers, C. M.; Liao, K.-C.; Yoon, H. J.; Rappoport, D.; Baghbanzadeh, M.; Simeone, F. C.; Whitesides, G. M. *Nano Lett.* **2014**, *14*, 3521.
- (15) Simeone, F. C.; Yoon, H. J.; Thuo, M. M.; Barber, J. R.; Smith, B. J.; Whitesides, G. M. *J. Am. Chem. Soc.* **2013**, *135*, 18131.
- (16) Barber, J. R.; Yoon, H. J.; Bowers, C. M.; Thuo, M. M.; Breiten, B.; Gooding, D. M.; Whitesides, G. M. *Chem. Mater.* **2014**, *26*, 3938.
- (17) 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.
- (18) Nerngchamnong, N.; Yuan, L.; Qi, D. C.; Li, J.; Thompson, D.; Nijhuis, C. A. *Nat. Nanotechnol.* **2013**, *8*, 113.
- (19) Tao, Y. T.; Wu, K. Y.; Huang, K. H.; Perng, T. P. *Org. Electron.* **2011**, *12*, 602.
- (20) Qiu, M.; Liew, K. M. *J. Phys. Chem. C* **2012**, *116*, 11709.
- (21) Tao, F.; Bernasek, S. L. *Chem. Rev.* **2007**, *107*, 1408.
- (22) Simmons, J. G. *J. Appl. Phys.* **1963**, *34*, 1793.
- (23) Simmons, J. G. *J. Appl. Phys.* **1963**, *34*, 2581.
- (24) de Boer, B.; Hadipour, A.; Mandoc, M. M.; van Woudenberg, T.; Blom, P. W. M. *Adv. Mater.* **2005**, *17*, 621.

- (25) Love, J. C.; Estroff, L. A.; Kriebel, J. K.; Nuzzo, R. G.; Whitesides, G. M. *Chem. Rev.* **2005**, *105*, 1103.
- (26) Dubois, L. H.; Nuzzo, R. G. *Annu. Rev. Phys. Chem.* **1992**, *43*, 437.
- (27) Slowinski, K.; Chamberlain, R. V.; Miller, C. J.; Majda, M. *J. Am. Chem. Soc.* **1997**, *119*, 11910.
- (28) Foti, G.; Sanchez-Portal, D.; Arnau, A.; Frederiksen, T. *J. Phys. Chem. C* **2013**, *117*, 14272.
- (29) Laibinis, P. E.; Whitesides, G. M.; Allara, D. L.; Tao, Y. T.; Parikh, A. N.; Nuzzo, R. G. *J. Am. Chem. Soc.* **1991**, *113*, 7152.
- (30) Srivastava, P.; Chapman, W. G.; Laibinis, P. E. *Langmuir* **2005**, *21*, 12171.
- (31) Tao, Y. T. *J. Am. Chem. Soc.* **1993**, *115*, 4350.
- (32) Colorado, R.; Lee, T. R. *J. Phys. Org. Chem.* **2000**, *13*, 796.
- (33) Cyganik, P.; Szelagowska-Kunstman, K.; Terfort, A.; Zharnikov, M. *J. Phys. Chem. C* **2008**, *112*, 15466.
- (34) Ramin, L.; Jabbarzadeh, A. *Langmuir* **2012**, *28*, 4102.
- (35) Aguilar-Sanchez, R.; Su, G. J.; Homberger, M.; Simon, U.; Wandlowski, T. H. *J. Phys. Chem. C* **2007**, *111*, 17409.
- (36) Stoliar, P.; Kshirsagar, R.; Massi, M.; Annibale, P.; Albonetti, C.; de Leeuw, D. M.; Biscarini, F. *J. Am. Chem. Soc.* **2007**, *129*, 6477.
- (37) Reus, W. F.; Nijhuis, C. A.; Barber, J. R.; Thuo, M. M.; Tricard, S.; Whitesides, G. M. *J. Phys. Chem. C* **2012**, *116*, 6714.
- (38) Paddonrow, M. N.; Shephard, M. J.; Jordan, K. D. *J. Phys. Chem.* **1993**, *97*, 1743.
- (39) Lin, L. L.; Jiang, J.; Luo, Y. *Physica E* **2013**, *47*, 167.
- (40) Cumming, G.; Fidler, F.; Vaux, D. L. *J. Cell Biol.* **2007**, *177*, 7.
- (41) Porter, M. D.; Bright, T. B.; Allara, D. L.; Chidsey, C. E. D. *J. Am. Chem. Soc.* **1987**, *109*, 3559.
- (42) Walczak, M. M.; Chung, C. K.; Stole, S. M.; Widrig, C. A.; Porter, M. D. *J. Am. Chem. Soc.* **1991**, *113*, 2370.
- (43) Lee, S.; Puck, A.; Graupe, M.; Colorado, R.; Shon, Y.-S.; Lee, T. R.; Perry, S. S. *Langmuir* **2001**, *17*, 7364.

(44) Bowers, C. M.; Liao, K.-C.; Žaba, T.; Breiten, B.; Baghbanzadeh, M.; Rappoport, D.; Krzykawska, A.; Aspuru-Guzik, A.; Cyganik, P.; Whitesides, G. M. *Submitted*.

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

(46) Mirjani, F.; Thijssen, J. M.; Whitesides, G. M.; Ratner, M.A.; *Submitted*.

(47) Alloway, D. M.; Hofmann, M.; Smith, D. L.; Gruhn, N. E.; Graham, A. L.; Colorado, R.; Wysocki, V. H.; Lee, T. R.; Lee, P. A.; Armstrong, N. R. *J. Phys. Chem. B* **2003**, *107*, 11690.

Table of content graphic.

