

Molecular Transport Junctions: An Introduction

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Guest Editors

Abstract

This issue of *MRS Bulletin* on molecular transport junctions highlights the current experimental and theoretical understanding of molecular charge transport and its extension to the rapidly growing areas of molecular and carbon nanotube electronics. This introduction will outline the progress that has been made in understanding the mechanisms of molecular junction transport and the challenges and future directions in exploring charge transport on the molecular scale. In spite of the substantial challenges, molecular charge transport is of great interest for its intrinsic importance to potential single-molecule electronic, thin-film electronic, and optoelectronic applications.

Keywords: carbon nanotubes, charge transport, molecular electronics, molecular junctions, optoelectronics, self-assembly.

Molecular Electronics: Definition and History

Molecular electronics is most simply defined as electronics whose behavior is dictated by the chemical, physical, and electronic structures of molecules. This definition is very broad; it includes conductive polymers and even the insulating polymer layers on metal wiring. In common use, molecular electronics refers to molecular structures whose characteristic features are on the nanoscale and that contain between one and a few thousand molecules. The simplest challenge involves determining the structure/function relationships for electronic transport (intra- or intermolecular) through a junction containing one or a few molecules as the transport medium and with either two (source/drain) or three (source/gate/drain) electrodes. Such transport structures are a dominant theme of contemporary molecular electronics and are the focus of this issue of *MRS Bulletin*.

The history of molecular electronics is brief. Some of the earliest work was performed at the laboratory of Hans Kuhn, working with Mann, Polymeropoulos, and Sagiv.¹ Using organic adlayers on solid substrates, this group reported some of the earliest (1971) reproducible electrical transport measurements through organic

molecules. They also developed some of the first effective self-assembly techniques for preparing structures in which molecules adhere to surfaces not by simple dispersion forces, but by molecular bond formation.

Following Kuhn's work, there were a number of important follow-up measurements.² In addition, there were some visionary (if perhaps premature) papers³ suggesting the use of single molecules as rectifiers and extensive device ideas involving molecular logic structures.⁴

The great step forward came in 1983, with the development of scanning probe microscopy (SPM).⁵ The capability to both manipulate and measure molecular structures topologically and spectroscopically prompted a renewed focus on the possibilities of molecular electronics. Continuing advances in synthesizing organic molecules with possible device applicability, and in their assembly and measurement, have led to increasing interest in the field and to substantial advances in our understanding.⁶

Starting roughly a decade after the invention of SPM, applications to molecular structures and their transport behavior ap-

peared. Important early work included the use of C_{60} as an electromechanical gate device,⁷ transport measurements on organic molecules with thiol end groups assembled between a gold surface and gold nanocrystals,⁸ and the introduction of break junction⁹ measurements to characterize currents in one (or a few) molecules.

Theoretical ideas for interpreting the current/voltage characteristics in molecular junctions began to appear in the 1990s. Some early approaches used the Landauer formulation,¹⁰ originally developed for semiconductor devices. In this simple picture, transport through molecular junctions is interpreted in terms of elastic scattering, and the conductance is given as the product of the quantized unit of conductance $(12.9 \text{ k}\Omega)^{-1}$ and a transmission coefficient describing how effective a molecule is in scattering the incoming electron from the upstream lead into the downstream lead. More powerful formulations, including the non-equilibrium Green's function (NEGF) approach, were also introduced in the mid-1990s.¹¹ Integrating a proper description of the molecule with an appropriate description of the leads is the challenge that these formulations face; the NEGF seems capable of including elastic and inelastic effects as well as vibronic (vibrational electron) coupling and system/bath interaction.

In this issue of *MRS Bulletin*, leading researchers provide a quick tour of some of the thematic areas of interest. In the first article, Hersam and Reifenger discuss charge transport through molecular junctions and provide a brief description of how to measure and interpret such transport behavior.

Ghosh et al. provide a theoretical overview of molecular charge transport structures. They introduce the different theoretical formulations, and provide guidance both for building understanding and interpreting experiments.

In the third article, Kushmerick et al. discuss conductance with different test beds and inelastic tunneling measurements.

In the last article, Avouris provides an introduction to carbon nanotube junctions, structures, transport, and devices.

Synthesis, Interpretation, and Device Aspects

In order to understand molecular structure/function relationships, it is necessary to synthesize appropriate molecules, fabricate (incorporate) them into a certain structure (junctions), and probe their behavior. Questions of structure and stability are crucial.

Both nature and synthetic chemistry have exploited the unique bonding character of

the carbon atom and a range of metal coordination environments to prepare a vast number of molecular systems. Routine bench-scale chemical synthesis produces 10^{23} molecules at a time, and each molecule is identical. Chemical functionalization of the molecules and van der Waals, π - π , covalent, and hydrogen bonding forces enable self-assembly of single molecules and molecular monolayers on surfaces. The diversity of molecular systems suggests the use of molecular materials in a wide range of applications (due to their structural and optical properties and processability) in packaging, mechanical, dye, passive and active optical, and resist technologies, and promises applications (arising from their electronic properties) in electrical and optoelectronic devices.

Carbon nanotubes (CNTs), discovered by Iijima in 1991, are frequently classified as "molecular" systems since their electronic structure is discrete. CNTs possess remarkable mechanical, electrical, optoelectronic, and thermal properties, as detailed in the following paragraphs. They are also thermally stable, making them compatible with Si processing and therefore particularly exciting for potential electronic and optoelectronic devices.

Understanding the correlation between molecular junction structure and electrical properties is of fundamental and technological interest. Fabricating molecular junctions less than ~ 10 nm in size presents a tremendous challenge and has made it difficult to compare reported measurements with theoretical work carried out to describe current flow in molecular junctions (see article in this issue by Ghosh et al.). Because CNTs can be much longer than small molecules, junctions with lengths ranging from the nanometer to the millimeter scales can be fabricated by standard lithographic techniques, and device structures can be studied to provide feedback between experimental and theoretical work. Since molecules and CNTs have many similarities, theoretical modeling of current flow in both molecule- and CNT-based junctions follows a generalized form of the Landauer theory. Insight into the electrical characteristics of molecular and CNT junctions and the influence of structure, conformation, interfaces with substrates or contacts, and environment is the first step in the pursuit of molecular-scale and CNT devices and is important to the improvement of thin-film organic electronic and optoelectronic devices.

The chemical diversity of molecular systems and the ability to synthetically tailor molecular structure has generated interest in molecular analogues of insulators, interconnects (wires), rectifiers, switches (transis-

tors), memory elements, and sensors. Similarly, metallic and semiconducting CNTs are exciting as potential interconnects, diodes, switches, memory elements, and sensors. More recently, molecular-scale and CNT electronic devices have received enormous attention, driven by the anticipation that conventional Si technology is running ever faster toward its scaling limits as the channel length of transistors has shrunk to the nanometer (<100 nm) size regime. Molecular-scale devices are expected to represent the ultimate in device scaling, as molecular lengths can be as small as ~ 1 nm, although limitations of tunneling and electrostatics, as in Si devices, set a lower bound on device dimensions (for the example of a molecular transistor, ~ 3 nm).

The simplicity of solution- or gas-phase self-assembly of molecular systems offers an opportunity for low-cost fabrication. Functionality that can be chemically tailored may provide for complexity in molecular devices that is not found in Si devices. For example, while scaling in Si devices is governed by pushing device dimensions ever smaller, in molecular devices it may be better to make larger molecules to achieve functionality and performance not found in Si devices. In CNT field-effect transistors (CNTFETs), the ballistic transport at small dimensions, reduced dimensionality, and the lack of dangling bonds that provides flexibility in interface/device design have led to promising demonstrations of device performance (see the article by Avouris in this issue).

Charge transport in molecular junctions is also important to the progress of thin-film organic devices such as light-emitting diodes (LEDs), photovoltaics (PVs), thin-film transistors (TFTs), and memory cells. The metal-molecule and metal-semiconductor junctions in each of these applications significantly limit the performance of thin-film molecular devices. Organic LEDs (OLEDs) have recently been commercialized in car radio displays and indicator lights and are being developed by many manufacturers for large-area displays. In OLEDs, charge injection across the molecule-metal interface requires high-voltage and, therefore, high-power operation and limits the stability and lifetime of devices. In organic and organic-inorganic PVs, recombination losses at metal-molecule and metal-semiconductor interfaces represent one of the biggest challenges to device efficiency. Similarly, in organic TFTs the molecule-contact interface presents electronic barriers to charge injection that give rise to current crowding at low voltage, measured as sublinear I - V characteristics in the triode region, and that necessitate higher device operating voltages.

Structure/Function Relationships

Molecular electronics entails at least two entities, the molecule and the electrode. From an energetic viewpoint, the molecular states are discrete molecular orbitals, while the electrodes (metallic or semiconducting) consist of bands characterized by continuous densities of states. The mix of discrete and continuous structures represents much of the challenge in understanding molecular electronic transport.

As indicated earlier, formulating the transport through the discrete structure requires a molecular Hamiltonian description and a Green's function description of the interaction of that molecule with the macroscopic leads.

When voltage is placed across the molecule, the electronic structure of the molecular species is no longer in equilibrium, although it can be in a steady state. The molecule tries to adjust to an electrochemical potential of one magnitude at the cathode side and another magnitude at the anode side; this causes some polarization within the molecule, which acts effectively as a polarized capacitor.

One of the reasons that CNTs are the most advanced areas of molecular electronics is that the community has a reasonably good understanding of their structure. Because CNTs can be prepared with lengths far exceeding a few nanometers, measurements can be (and have been, see Figure 1) made of the nature of the electrostatic potential across the CNT, and of the approximate CNT geometries. For junctions containing organic molecules—in particular, the very popular thiol/gold structural motif—we have no direct structural evidence concerning the geometry. This makes calculations and mechanistic deduction quite complex. Indeed, understanding the structure will be crucial if the kinds of structure/function relationships that are of primary interest in molecular electronic junctions are to be compared directly to experiment. Although the structures are generally only crudely understood, there have been some major advances in our understanding of how molecular behavior influences transport in junctions. Highlights of these advances include the following:

1. The comparison between the rate constant (the rate at which electrons would transfer from a donor at one end of a molecular bridge to an acceptor at the other end) and the conductance through that same molecular bridge has been clarified.¹² This permits interesting aspects of the mechanism—such as the transition between coherent and incoherent transport as a function of either length or temperature—to be compared.

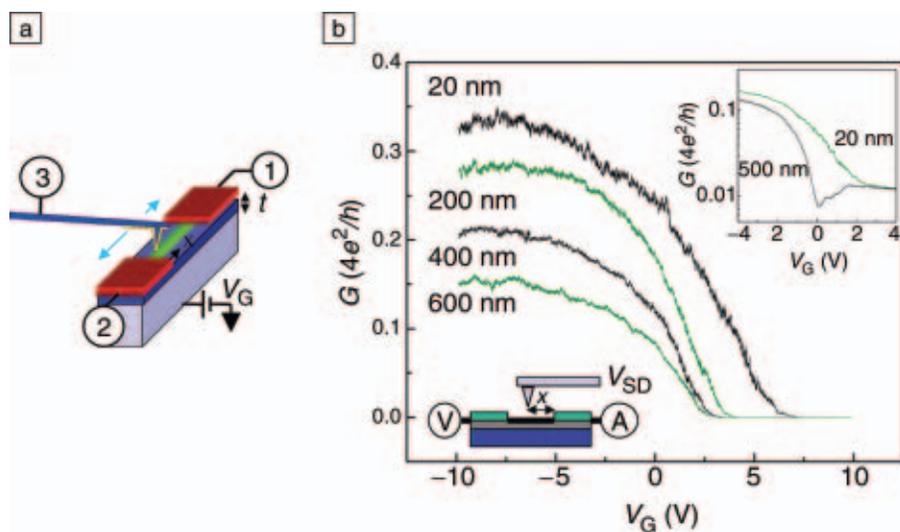


Figure 1. (a) A carbon nanotube transistor (channel length, $1.2 \mu\text{m}$; nanotube diameter, 2 nm ; $t =$ gate oxide thickness; V_G is the applied gate voltage). A conductive atomic force microscope (AFM) probe is positioned over the device to study the channel length dependence of the device characteristics and the electrostatics and contacts of the device. Electrodes, marked (1) and (2), and the AFM tip (3) can serve as the voltage source, current probe, or voltage probe in the measurements. (b) The measured channel-length-dependent conductance (in units of the quantum conductance), as a function of V_G , where x is the channel length, $V_{ip} = 100 \text{ mV}$, and $t = 500 \text{ nm}$.²⁰ V_{SD} is the source–drain voltage. Similarly (inset), the characteristics of a second device are plotted on a log scale, where $t = 200 \text{ nm}$. (Reprinted with permission from Reference 20.)

2. The importance of covalent interactions at the molecule/metal interface (effectively reducing the Schottky barriers and permitting more control of the molecular levels by the applied voltage) has been clarified.¹³ In nanotubes, true ohmic junctions (for p -type transport) apparently can be prepared¹⁴ using palladium as the electrode material.

3. The importance of molecular recognition behavior in the construction of junctions and in preparing both adlayers and specific quantum dot junctions is now understood.

4. Dynamical stereochemistry of molecules has been used as the basis for both modeling¹⁵ and experimental demonstration¹⁶ of memory and switching applications. This stereochemical variation is one of the unique properties of molecules that most strongly differentiates molecular from more traditional semiconductor electronics.

5. A comparison has been made of transport through junctions containing single molecules with transport through those based on molecular adlayer films; once again, the results highlight the crucial role that contacts play in molecular junction transport. In particular, a substantial reduction in contact resistance has been demonstrated using covalent interactions at carbon electrodes;¹⁷ less effective mixing occurs through Lewis interactions at metal/thiol or isocyanide links.

6. The importance of the electrostatic potential and its control has been demonstrated clearly, both in measurements and models.

7. Gating due to molecular geometric change is going to be general at ambient temperature, simply because molecules do move at room temperature. Such gating can completely dominate the measured I - V behavior. If controlled, such gating may lead to interesting device applications,^{15,16,18} both in two-electrode and three-electrode configurations.

8. Specific device applications, both in simple molecular transport junctions and in such areas as molecular sensing and molecular optoelectronics, have been widespread and impressive. The great sensitivity of transport through molecular junctions to the electrostatic potential suggests that sensing using transport modification is effective and powerful.

Elegant recent work by Ho and his collaborators,¹⁹ discussed in the article by Hersam and Reifengerger, demonstrates the capability of current techniques to assemble junctions on an atom-by-atom basis and then characterize the local densities of states using transport perpendicular to the molecular axis. Extending this understanding to the charge transport behavior, and providing comparably detailed structure/function relationships, represents perhaps

the greatest challenge to our understanding of molecular junctions.

CNT and Molecular Behaviors

Developing a further understanding of the electronic characteristics and fabrication of molecular- and CNT-based junctions and devices presents unique challenges.

The electronic properties of CNTs have been studied by scanning probe microscopies and optical spectroscopies. Figure 1 shows a CNTFET in which the lithographically defined $1.2 \mu\text{m}$ channel length is large enough for a conductive AFM probe to measure the channel length dependence of the device characteristics, electrostatics, and contacts.²⁰ CNTs are being aggressively explored to understand the characteristics of different species of nanotubes, their contact physics, and environmental influences, and to engineer high-quality CNT devices.

Present synthesis routes typically prepare batches of CNTs containing both semiconducting and metallic tubes (determined by their chirality) with a range of diameters. Work has proceeded on functionalizing CNTs with organic molecules in an effort to solubilize them, to separate different species of CNTs, to place the tubes on surfaces, and to electronically manipulate or dope them. While considerable progress has been made in regard to chemical manipulation and synthetic routes, processing to separate and position CNTs presents major challenges to the integration and fabrication of CNT junctions and devices.

In contrast to CNTs, while molecules can be synthesized and self-assembled from solution onto surfaces, the nanometer length scale of molecules makes the study and device fabrication of molecular junctions very challenging. SPM (see Hersam and Reifengerger) offers the resolution and control to characterize single molecules and molecular monolayers on surfaces. SPM has been used to probe the dynamics of molecular conductance on surfaces. Derivatives of 2,5-di(phenylethynyl)-4',4''-thio)benzene (the nitro/amine derivative showed negative differential resistance in vertical structures)²¹ and, more recently, alkanedithiol molecules (Figure 2)²² show stochastic switching. Researchers are using SPM to close in on the origin of conductance modulations of molecules on surfaces. Both recent observation of switching in alkanedithiols and computations of the energetics and transport properties of differing junction geometries suggest that the thiol-Au contact may be responsible for the observed fluctuations.

While SPM provides well-controlled junctions and measurements of electron density and density of states, the junctions

consist of one chemical contact and one tunneling contact, so SPM does not directly measure junction conductance. Mechanically controllable break (MCB) junctions, as shown in Figure 3,²³ have been used⁹ to make two chemical contacts to a single molecule and measure transfer in molecular junctions. MCB junctions are formed using piezoelectrics to push on the fabricated metal structure, controllably breaking the junction, and to vary the separation between the metal tips. The I - V characteristics of some molecular MCB junctions are similar to theoretical calculations and are molecule-specific. The I - V characteristics are stable for many voltage sweeps, but are unstable over longer times, as seen by the different features in the two sets of characteristics collected on the same sample. In effect, the two sets of characteristics represent different molecular junctions, as the junction is broken and remade at the contacts, creating a different spectral density for the molecule in the junction.

Scanning probe microscopy and MCB junctions cannot be integrated into device geometries. Two-terminal vertical sandwich structures, as shown in Figure 4, were first used to fabricate molecular monolayer junctions and can be fabricated in a crossbar geometry. Monolayer junctions are prepared by assembling the molecules onto a bottom electrode and depositing a top metal electrode, where in principle the monolayer height defines the electrode separation. Molecular monolayer junctions in this geometry have shown low leakage for insulating molecules, rectification in donor-acceptor molecules (Figure 4),²³ and negative differential resistance/switching in some conjugated molecules. The clear drawback of vertical sandwich structures is that the top metal electrode is deposited on the molecules and may partially or completely penetrate or react with the monolayer, depending on the choice of metal. For metal-molecule-metal structures, this often results in junctions with I - V characteristics that are shorted or that have been misinterpreted. For metal-molecule-semiconductor junctions, length-dependent electrical characteristics have been measured for densely packed alkyl monolayers, suggesting that the monolayer coverage is sufficiently dense to mask direct metal-Si pathways.²⁴

Concern over top metal deposition and the limitation of providing only two terminal measurements has led to the pursuit of lateral junction geometries. Recently, electromigration has been used²⁵ to open up ~ 1 nm spacing at the constriction in metal lines, as shown in Figure 5. The semiconductor support provides a third, although distant (relative to the source-drain spacing) and therefore weakly cou-

pled, gate electrode. Organometallic and organic molecules and small metal clusters have been measured in these junctions. Low-temperature I - V characteristics are highly non-ohmic, consistent with Coulomb blockade (conductance gaps dominated by single-particle charging energy), and Kondo resonance (zero bias conductance, believed to originate from the spin and orbital degrees of freedom in the metal centers). The junctions formed by electromigration or electrochemistry provide a new platform with ~ 1 nm gaps for studying the electrical behavior of single small-molecule systems.

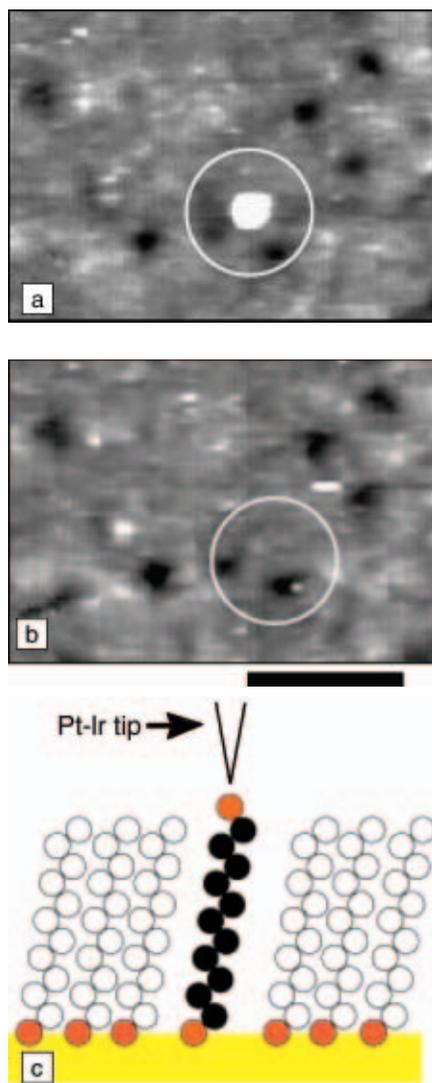


Figure 2. (a), (b) Scanning probe micrographs of alkanedithiols inserted in an alkanedithiol monolayer assembled on Au (c). The size bar is 10 nm. Stochastic switching is observed as the octanedithiols blink on (a) and off (b). (Reprinted with permission from Reference 22.)

Instead of pushing the dimensions of the channels to ~ 1 nm separations, recent work²⁶ has used e-beam lithography to prepare reproducible junctions and chemistry to bridge the separation between the electrodes, as shown in Figure 6. This

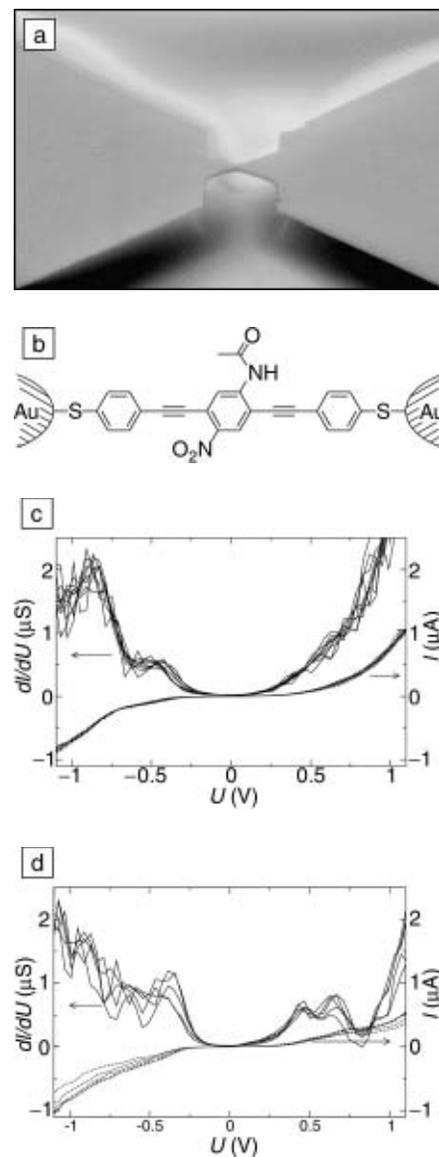


Figure 3. (a) Scanning electron micrograph of a mechanically controllable break junction used to measure the conductance of 1,4-bis(2'-paramecaptophenyl)-ethynyl-2-acetyl-amino-5-nitro-benzene. (b) Chemical structure. (c), (d) The I - V characteristics (right axis) and the numerically differentiated dI/dU (left axis) values are shown for (c) a junction repeatedly scanned and (d) a subsequent junction after reconfiguration of the molecules between the metal electrodes. (Reprinted with permission from Reference 23.)

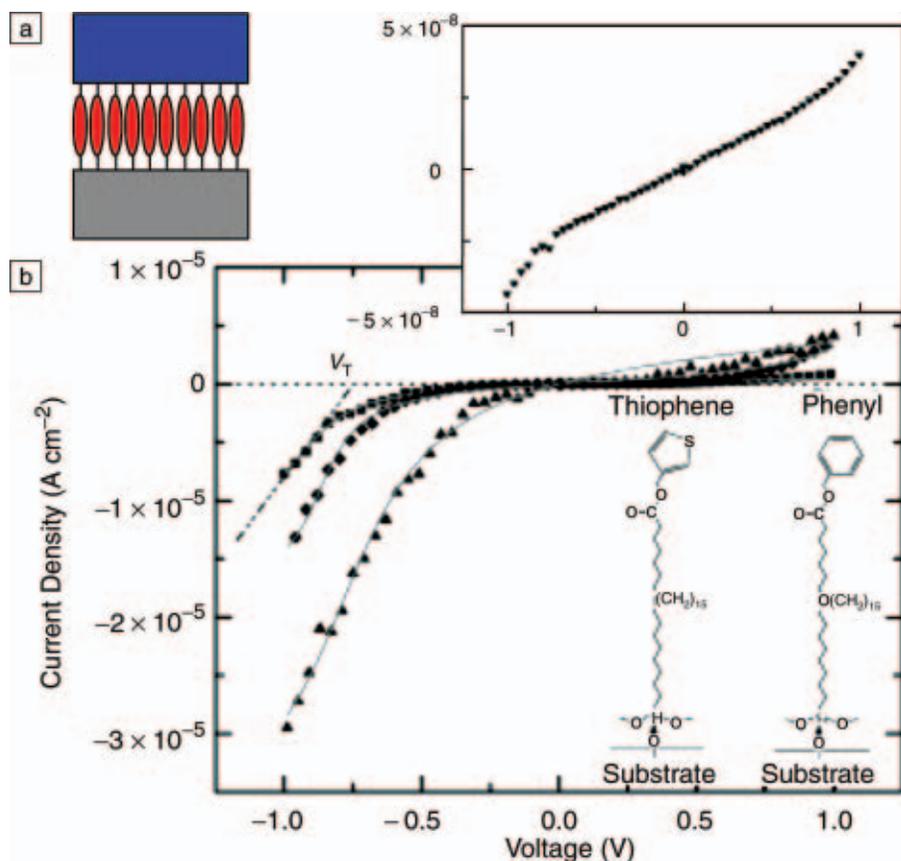


Figure 4. (a) Schematic illustration of a two-terminal vertically fabricated junction. (b) I - V characteristics showing rectification of a thiophene-terminated oct-7-en-1-trichlorosilane self-assembled monolayer (triangles), and phenyl-terminated (squares) and thiophene-terminated (diamonds) heptadec-16-en-1-trichlorosilane self-assembled monolayers, in a molecular junction between Al and n^+ Si electrodes. The top graph shows the graphical determination of the threshold voltage. V_T is taken as the intercept of the linear extrapolation of the I - V curve and the zero of the y axis. (Reprinted with permission from Reference 24.)

approach also allows a gate to be placed in proximity to the junction, allowing penetration of the gate field in the channel. This approach was demonstrated for metal-metal coordination compounds by templating the assembly of the compounds off the electrodes, using thiol chemistry, and adding molecules layer-by-layer to bridge the channel. I - V characteristics show consistent reversible traces at low voltage and a single, irreversible negative differential resistance at high voltage.

These examples illustrate the many approaches being pursued to understand molecular junctions and highlight some important future directions. Thiol chemistry on Au or carboxylic acids and silanes on SiO_2 have been the most heavily studied systems, largely for historical reasons. Many studies suggest that instability in the Au-thiol contact may give rise to observed I - V characteristics, pointing to the importance of controlling the self-assembly using the many functionalities provided by chemistry. Nearly all schemes to create molecular junctions lack information regarding the geometry of the molecule(s) in the junctions, making it almost impossible to correlate the molecule-junction structure with its I - V characteristics. Overcoming this limitation requires new tools to address the molecular-scale geometry, as well as continued improvement and new ideas to fabricate reproducible and reliable molecular-scale junctions.

The fields of molecular and carbon nanotube junctions, while presenting different research challenges, are yielding an exciting fundamental understanding of their

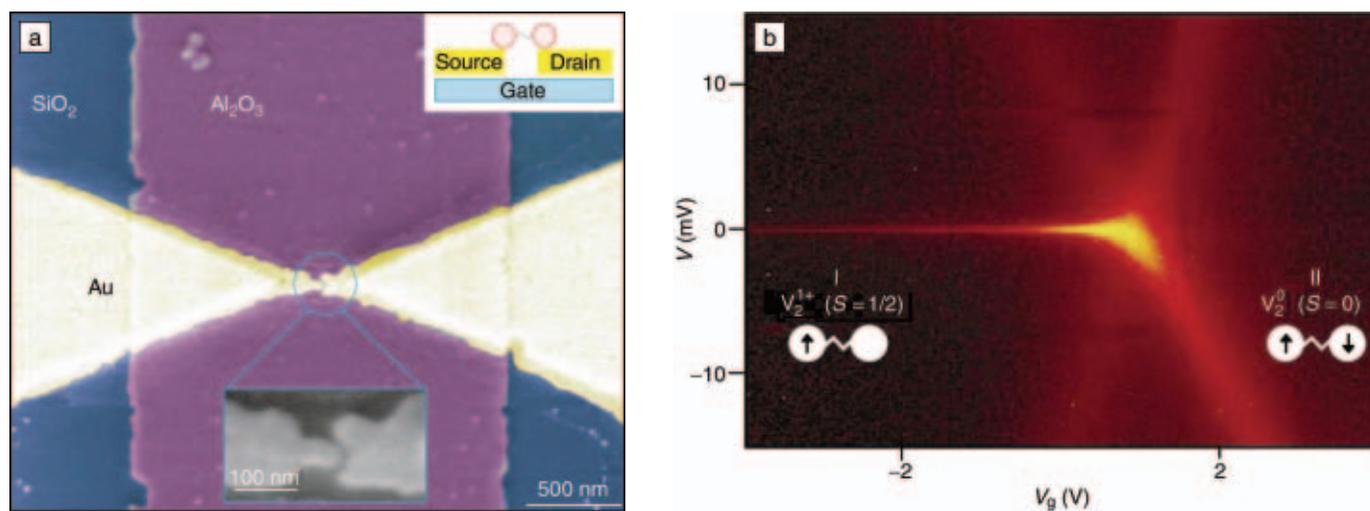


Figure 5. (a) Schematic illustration and enlarged scanning electron micrograph (inset) of a transistor structure (channel length, ~ 1 nm) formed by electromigration of Au electrodes deposited on a 3 nm Al_2O_3 gate dielectric with an Al gate. (b) Differential conductance ranges from zero (dark red) to $1.55\text{ e}^2/h$ (bright yellow) as a function of bias and gate voltages. I and II indicate two conductance gap regions, and the diagrams illustrate the corresponding charge and spin states of the divanadium molecule in each region. (Reprinted with permission from Reference 25.)

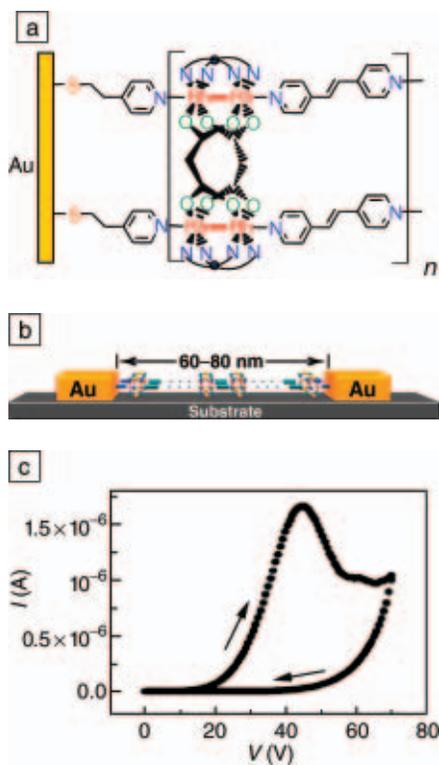


Figure 6. (a) Layer-by-layer assembly of metal-metal bonded coordination compounds templated from source and drain electrodes. (b) Schematic illustration of a metal-metal bonded coordination compound spanning Au electrodes. (c) Measured I - V characteristics after the assembly bridges the ~ 80 nm channel. Arrows indicate the measured current for the up and down swing in applied voltage. (Reprinted with permission from Reference 26.)

properties. While the science of these systems must come first, molecular and CNT junctions promise intriguing future applications.

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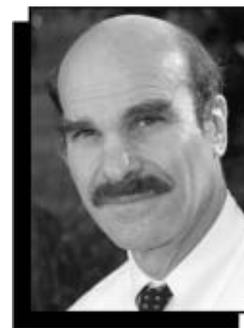
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References

1. B. Mann and H. Kuhn, *J. Appl. Phys.* **42** (1971) p. 4398; E.E. Polymeropoulos and J. Sagiv, *J. Chem. Phys.* **69** (1978) p. 1836; L. Netzer and J. Sagiv, *J. Am. Chem. Soc.* **105** (1983) p. 674.
2. A. Leger, J. Klein, M. Belin, and D. Defourne, *Thin Solid Films* **8** (1971) p. R51.
3. A. Aviram and M.A. Ratner, *Chem. Phys. Lett.* **29** (1974) p. 277.
4. F.L. Carter, R.E. Siatkowski, and H. Wohltjen, eds., *Molecular Electronic Devices: Proc. 3rd Intl. Symp. on Molecular Electronic Devices* (North-Holland, New York, 1989).
5. G. Binning, H. Rohrer, C. Gerber, and E. Weibel, *Phys. Rev. Lett.* **49** (1982) p. 57.
6. M.C. Petty, M.R. Bryce, and D. Bloor, *Introduction to Molecular Electronics* (Oxford University Press, Oxford, 1995); C.A. Mirkin and M.A. Ratner, *Annu. Rev. Phys. Chem.* **43** (1992) p. 719; A. Aviram, ed., *Molecular Electronics—Science and Technology* (American Institute of Physics, College Park, MD, 1992); A. Aviram, M.A. Ratner, and V. Mujica, eds., *Ann. N.Y. Acad. Sci.* **852** (1998); J. Jortner and M.A. Ratner, eds., *Molecular Electronics* (Blackwell Science, Cambridge, MA, 1997); C. Joachim, J.K. Gimzewski, and A. Aviram, *Nature* **408** (2000) p. 541; M.A. Ratner and M.A. Reed, *Encyclopedia of Science and Technology*, 3rd ed., Vol. 10 (Academic Press, New York, 2002); V. Mujica and M.A. Ratner, in *Handbook of Nanoscience, Engineering and Technology*, edited by W.A. Goddard III, D.W. Brenner, S.E. Lyshevski, and G.J. Iafrate (CRC Press, Boca Raton, FL, 2002); C. Joachim, J.K. Gimzewski, and A. Aviram, *Nature* **408** (2000) p. 541; P. Hänggi, M. Ratner, and S. Yaliraki, eds., *Chem Phys.* **281** (2002); M.A. Reed and T. Lee, eds., *Molecular Nanoelectronics* (American Scientific Publishers, Stevenson Ranch, CA, 2003).
7. C. Joachim, J.K. Gimzewski, R.R. Schlitter, and C. Chavy, *Phys. Rev. Lett.* **74** (1995) p. 2102.
8. M. Dorogi, J. Gomez, R. Osifchin, R.P. Andres, and R. Reifengerger, *Phys. Rev. B* **52** (1995) p. 9071.
9. M.A. Reed, C. Zhou, C.J. Miller, T.P. Burgin, and J.M. Tour, *Science* **278** (1997) p. 252; H.B. Weber, J. Reichert, F. Weigend, R. Ochs, D. Beckmann, M. Mayor, R. Ahlrichs, and H. von Löhneysen, *Chem. Phys.* **281** (2002) p. 113; and C. Kergueris, J.P. Bourgoin, S. Palacin, D. Esteve, C. Urbina, M. Magoga, and C. Joachim, *Phys. Rev. B* **59** (1999) p. 12505.
10. V. Mujica, M. Kemp, and M.A. Ratner, *J. Chem. Phys.* **101** (1994) p. 6849.
11. S. Datta, *Electronic Transport in Mesoscopic Systems* (Cambridge University Press, Cambridge, UK, 1995); W. Tian, S. Datta, S.H. Hong, R. Reifenberger, J.I. Henderson, and C.P. Kubiak, *J. Chem. Phys.* **109** (1998) p. 2874.
12. A. Nitzan, *Ann. Rev. Phys. Chem.* **52** (2001) p. 681.
13. Y. Xue, S. Datta, and M.A. Ratner, *J. Chem. Phys.* **115** (2001) p. 4292.
14. D. Mann, A. Javey, J. Kong, Q. Wang, and H.J. Dai, *Nano Lett.* **3** (2003) p. 1541.
15. A.W. Ghosh, T. Rakshit, and S. Datta, arXiv.org e-print archive, cond-mat/0212166 (accessed March 2004); P.E. Kornilovitch, A.M. Bratkovsky, and M.S. Williams, *Phys. Rev. B* **66** 245413 (2002); A. Troisi and M.A. Ratner, *J. Am. Chem. Soc.* **124** (2002) p. 14528.
16. E.W. Wong, C.P. Collier, M. Behloradsky, F.M. Raymo, J.F. Stoddart, and J.R. Heath, *J. Am. Chem. Soc.* **122** (2000) p. 5831.
17. R. McCreery, J. Dieringer, A.O. Solak, B. Snyder, A.M. Nowak, W.R. McGovern, and S. DuVall, *J. Am. Chem. Soc.* **125** (2003) p. 10748.
18. J. Chen, J. Su, W. Wang, and M.A. Reed, *Physica E* **16** (2003) p. 17.
19. G.V. Nazin, J.R. Hahn, and W. Ho, *Science* **302** (2003) p. 77.
20. Y. Yaish, J.-Y. Park, S. Rosenblatt, V. Sazonova, M. Brink, and P.L. McEuen, *Phys. Rev. Lett.* **92** 046401 (2004).
21. Z.J. Donhauser, B.A. Mantooth, K.F. Kelly, L.A. Bumm, J.D. Monnell, J.J. Stapleton, D.W. Price Jr., A.M. Rawlett, D.L. Allara, J.M. Tour, and P.S. Weiss, *Science* **292** (2001) p. 2303.
22. G.K. Ramachandran, T.J. Hopson, A.M. Rawlett, L.A. Nagahara, A. Primak, and S.M. Lindsay, *Science* **300** (2003) p. 1413.
23. J. Reichert, R. Ochs, D. Beckmann, H.B. Weber, M. Mayor, and H.v. Löhneysen, *Phys. Rev. Lett.* **88** 176804-1 (2002).
24. S. Lenfant, C. Krzeminski, C. Delerue, G. Allan, and D. Vuillaume, *Nano Lett.* **3** (2003) p. 741.
25. J. Park, A.N. Pasupathy, J.I. Goldsmith, C. Chang, Y. Yaish, J.R. Petta, M. Rinkoski, J.P. Sethna, H.D. Abruña, P.L. McEuen, and D.C. Ralph, *Nature* **417** (2002) p. 722; W. Liang, M.P. Shores, M. Bockrath, J.R. Long, and H. Park, *Nature* **417** (2002) p. 725.
26. C. Lin and C.R. Kagan, *J. Am. Chem. Soc.* **125** (2003) p. 336. □



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He has received the Kolthoff Prize, the Humboldt Award, and the Israel Chemical Society Prize. He is a fellow of the American Physical Society and the American Association for the Advancement of Science.

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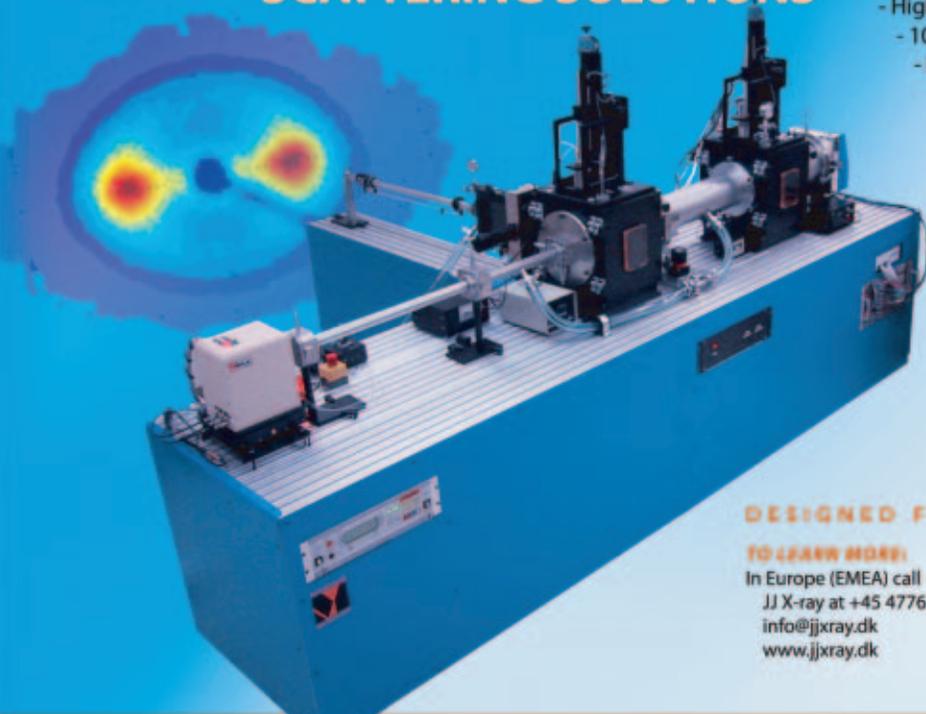
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