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Brandbyge, Mads; Stokbro, Kurt; Taylor, Jeremy Philip; Mozos, José-Luis; Ordejó, Pablo

Published in:
Physical Review B Condensed Matter

Link to article, DOI:
10.1103/PhysRevB.67.193104

Publication date:
2003

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

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The failure of interconnects in integrated circuits is often due to directionally biased diffusion of atoms caused by the presence of an electric current (electromigration).1 In recent years the prospect of electronic devices operating essentially on the atomic/molecular scale has gained significant interest,2 and electromigration and current-induced conformational changes are important issues when downscaling electronic components to these sizes.3 A single atom wide gold contact is among the simplest atomic scale conductors and therefore ideal for fundamental studies of the current-induced forces. It is remarkable that these systems can sustain voltages up to several volts before breaking.4–6

Our aim here is to uncover the microscopic origin of the current-induced bond weakening/strengthening in an atomic gold wire. We analyze state-of-the-art first principles calculations of atomic gold wires connected to two gold electrodes with different electrochemical potentials. We find that current induced forces are closely related to the chemical bonding, and arise from the rearrangement of bond charge due to the current flow. We explain the current induced bond weakening/strengthening by introducing bond charges decomposed into electrode components.

When the voltage is applied we observe a substantial redistribution of the electronic charge. At 0 V the wires have a net negative charge of about 0.2 excess electrons. About half of this resides on atom 2. At 2 V the excess electrons on atom 2 are almost halved. This charge redistribution results in an asymmetric voltage drop where the main drop is between the negative electrode and atom 2 (see Fig. 1).

In Fig. 2(a) we show the calculated bond forces for the (100)/(111) wires with atomic positions fixed at the relaxed values15 obtained for zero bias. We find that the forces on the symmetric atoms 1 and 3 roughly follow each other, also beyond the linear bias regime.3 We note that the order of magnitude and direction of the bond forces at 2 V are similar for (100)/(111) while the detailed behavior differs: the bond forces for the (100) wire stay linear up to 1 V and level off around 2 V while we observe an onset of the bond forces for (111) at 1 V. The magnitude of the bond forces of the order of 1–1.5 nN for 1–2 V is sizable compared to the force required to break a one-atom thick wire ~1.5 nN.16

Along with the bond force we also show the overlap population (OP) in Fig. 2(a). The OP is a measure of the

FIG. 1. (a) Direction of forces and voltage drop for the gold wire connecting (100) electrodes at 1 V bias. (b) Isodensity surfaces for the change in density from 0 to 1 V. Dark is deficit and white is extra electron density. The solid (dotted) surface correspond to \( \pm 5 \times 10^{-4} e/\text{Å}^3 \) (\( \pm 2 \times 10^{-4} e/\text{Å}^3 \)).

Origin of current-induced forces in an atomic gold wire: A first-principles study

Mads Brandbyge,1,* Kurt Stokbro,1 Jeremy Taylor,1 José-Luis Mozos,2 and Pablo Ordejón2

1Mikroelektronik Centret (MIC), Technical University of Denmark, Bldg. 345E, DK-2800 Lyngby, Denmark
2Institut de Ciencia de Materials de Barcelona, CSIC Campus de la U.A.B., 08193 Bellaterra, Spain

(Received 10 December 2002; published 20 May 2003)

We address the microscopic origin of the current-induced forces by analyzing results of first principles density functional calculations of atomic gold wires connected to two gold electrodes with different electrochemical potentials. We find that current induced forces are closely related to the chemical bonding, and arise from the rearrangement of bond charge due to the current flow. We explain the current induced bond weakening/strengthening by introducing bond charges decomposed into electrode components.

DOI: 10.1103/PhysRevB.67.193104

PACS number(s): 73.40.Jn, 66.30.Qa, 87.15.By
electronic charge residing in the bond. We note that except for the (111) wire at low bias, the force and OP curves are almost mirrored. The result that an increase (decrease) in bond charge makes the bond force compressive (repulsive) is what we expect intuitively. In Fig. 2(b) we show the bond lengths after subsequent relaxation of the wire atoms for finite bias. The main relaxations take place in the wire bonds with smaller displacements in the wire-electrode bonds.

We aim at an qualitative understanding of the results for the dependence of the force on the voltage bias. To this end we focus on the OP. We can express\(^\dagger\) the force acting on atom \(i\) due to the valence electrons using the force operator \(\hat{F}_i\) and the density matrix \(\hat{D}\),

\[
\hat{F}_i = \text{Tr}[\hat{F}_i \hat{D}], \quad \text{where} \quad \hat{F}_i = -\frac{\partial H}{\partial R_i}. \tag{1}
\]

Consider the bonding between two atoms represented by orbitals \(|\phi_1\rangle\) and \(|\phi_2\rangle\) and separated by bondlength \(b\). From Eqs. (1) we get the bond force,

\[
F_{\text{bond}} = -2 \left\langle \phi_2 | H' | \phi_1 \right\rangle \left\langle \phi_2 | \phi_1 \right\rangle O_{12}, \quad H' = \frac{\partial H}{\partial b}, \tag{2}
\]

where we assume that only the hopping element, \(\left\langle \phi_2 | H | \phi_1 \right\rangle\), changes with \(b\). The bond force is proportional to the OP for the 12 bond

\[
O_{12} = 2S_{12}D_{12}. \tag{3}
\]

The OP is typically taken as a simple measure of the strength of a chemical bond as suggested by Mulliken for molecules.\(^\dagger\) For extended systems the density matrix can be expressed in terms of the density of states (DOS) matrix, \(\rho\). In equilibrium we have

\[
O_{12} = 2S_{12} \int_{-\infty}^{\infty} d\varepsilon \rho_{12}(\varepsilon) n_F(\varepsilon - E_F), \tag{4}
\]

where \(n_F\) and \(E_F\) is the Fermi function and energy. The contribution from states at different energy(\(\varepsilon\)) in the extended system to the bonding between the two orbitals is described qualitatively by the OP weighted DOS (OPWDOS) or COOP curve \(2S_{12}\rho_{12}(\varepsilon)\) as discussed by Hoffmann.\(^\dagger\)

Now we consider the nonequilibrium situation where an electrical current is running though a contact connecting two reservoirs, left and right (\(L, R\)), with different chemical potentials (\(\mu_L, \mu_R\)). The contact contains the 12 bond. In this case the bond force will change since the density and Hamiltonian matrices deviate from equilibrium values. The appropriate density matrix for the nonequilibrium situation is constructed from scattering states, and the total spectral density matrix (\(\rho\)) is split into partial contributions corresponding to their left (\(\rho^L\)) or right (\(\rho^R\)) origin (see, e.g., Ref. 10),

\[
\rho(\varepsilon) = \rho^L(\varepsilon) + \rho^R(\varepsilon). \tag{5}
\]

The density matrix for nonequilibrium is then found by filling the left and right originating states according to the respective chemical potentials\(^\dagger\).

\[
D = \int_{-\infty}^{\infty} d\varepsilon \rho^L(\varepsilon) n_F(\varepsilon - \mu_L) + \rho^R(\varepsilon) n_F(\varepsilon - \mu_R). \tag{6}
\]

We split the overlap population(Eq. 4) further into its partial left and right components

\[
O_{12} = O_{12}^L + O_{12}^R, \tag{7}
\]

where

\[
O_{12}^L = 2S_{12} \int_{-\infty}^{\infty} d\varepsilon \rho_{12}^L(\varepsilon) n_F(\varepsilon - \mu_L), \tag{8}
\]

and likewise for \(R\). When more orbitals are involved on atom 1 and 2 the overlap populations can be broken down in orbital components. In this case each orbital overlap will contribute with different weight to the bond force according to their different force matrix elements \(H'\). This complication, together with the neglect of change in \(H'\) with applied voltage, makes the bond force and OP only roughly proportional.
as we observe for the gold wires in Fig. 2. However, as a first approximation, we can explain the observed change in bond forces from the change in OP, which in turn means the change in left ($\Delta O^L$) and right ($\Delta O^R$) contributions.

In Fig. 3 we consider the change from 0 V to 1 V in left and right OP of the 12 and 23 bonds for the (100) case [we see a quite similar pattern for (111)]. For both bonds $\Delta O^L$ is negative (decreasing bonding) while $\Delta O^R$ is positive (increasing bonding). We have resolved these further into the orbitals on atom 2 and display the main contributions in Fig. 3.

In order to understand the physics involved we present in Fig. 4(a) a simple picture. In the presence of current the electrons from the left electrode populate states above the original Fermi energy $E_F$. These populate bonding or antibonding states depending on the position of $E_F$. Likewise there is a depopulation in electrons from the right. To make this picture more explicit we consider in Fig. 4(b) a single bond between two atoms each with a single atomic level $e_L$ and $e_R$. The levels couple via a matrix element $t<0$, and an overlap $S>0$, and form bonding/antibonding orbitals $e_B$ and $e_A$. The left and right electrodes modeled by a level broadening $\Gamma_L$ of the left level and $\Gamma_R$ for the right. For this bond the resulting partial DOS due to the states originating from the left is

$$\rho^L(\varepsilon) = \frac{2}{\pi} \frac{\Gamma_L(\varepsilon - e_L)(e_S + |t|)}{[(1-S^2)(e-e_A)(e-e_B) - \Gamma_L \Gamma_R]^2 + [\Gamma_R(e-e_L) + \Gamma_L(e-e_R)]^2}.$$  

We note that (i) $\rho^R$ is found by exchanging $L \rightarrow R$. (ii) $\rho^L$ is proportional to the coupling $\Gamma_L$. (iii) the crossover between bonding (positive) and antibonding (negative) is given by the position of $e_R$. From (i), (iii) we see that $\rho_L$ contains more antibonding character than $\rho_R$ when $e_L > e_R$.

We have plotted $L/R$ COOP curves in Figs. 4(c)–4(e) for different fillings and $\Gamma_L = \Gamma_R$. In the top row we assume that there is no voltage drop between the atoms $\varepsilon_L = \varepsilon_R$. Here the change in OP comes entirely from the change in filling due to the shift of $\mu_L$ and $\mu_R$ away from the equilibrium $E_F$ [Eq.
(8)]. For almost filled states [Fig. 4(c), top] the lowering of $\mu_R$ deplete states with antibonding character and $O^R$ increases. The increase in $\mu_L$ leads to a decrease in $O^L$ which does not balance the increase in $O^R$. The net effect is a decrease in antibonding character and strengthening of the bond. When the states are almost empty [Fig. 4(e), top] we also observe a strengthening since now $O^L$ increases more than $O^R$ is decreasing. For a bond initially with maximal strength [Fig. 4(d), top] and, in general, for $E_F$ located in a region where the COOP decreases, the bond weakens since both $O^R$ and $O^L$ decrease.

In the bottom row of Figs. 4(c)–4(e) we assume that the full voltage drop takes place between the two atoms $\varepsilon_L - \varepsilon_R = \mu_L - \mu_R > 0$. The bonding peak becomes dominating in the right COOP and likewise for the antibonding peak in the left COOP. The net result is less bond strengthening in (c) and (e), and more bond weakening in (d). The largest effect of a voltage drop is seen for half filling [Fig. 4(d), bottom], where a large negative $\Delta O_L$ occurs because the bonding peak decreases and at the same time more anti-bonding states are being occupied.

In summary, for equal coupling, $\Gamma_L = \Gamma_R$, our simple model yield (i) bond strengthening for almost empty/filled states, (ii) bond weakening for about half filled states, and (iii) a bond with a voltage drop is weaker than it would be without a drop. When the bond is not coupled equally well to left and right, $\Gamma_L \neq \Gamma_R$, the left and right overlap contributions have to be weighted accordingly.

In the case of the gold wires we can to a good approximation assume that the $d_{yz}$, $d_{zx}$, and $p_z$ orbitals on atom 2 only couple with the corresponding orbital on atom 1 and 3. The $d_{yz}, d_{zx}$ states are almost filled and match the case in Fig. 4(c): $\Delta O^R > 0$ while $\Delta O^L < 0$. On the other hand the $p_z$ states are almost empty and match the situation in Fig. 4(e): $\Delta O^L > 0$ while $\Delta O^R < 0$. This is exactly the behavior we observe in Fig. 3. For the $s$ orbitals, which are slightly more than half-filled, we can expect a decrease in $O^L$, which will be especially pronounced if a voltage drop takes place in the bond [see Fig. 4(d), bottom]. This is also what we observe for the 12 bond in Fig. 3.

Based on our simple model we see that the almost completely filled states (d) and slightly more than half-filled states (s) together yield a decrease in $O^L$ and increase in $O^R$. Since bond 12 couple more to the left electrode the total change in $O^L$ will be bigger than the change in $O^R$. This explains the bond weakening of bond 12. The opposite is the case for bond 23. Also the voltage drop taking place in bond 12 will weaken this bond with respect to bond 23.

In conclusion we have analyzed first principles calculations of the current-induced forces in an atomic gold wire. We have shown that the current-induced forces are due to a shift in the population of bonding and antibonding levels, and can be explained by examining the change in electrode decomposed bond charges (overlap population) with applied voltage. Although we have concentrated on a simple system the approach should apply to atomic scale conductors in general.

We acknowledge support from the Danish Research Councils (M.B. and K.S.), European Union (SATURN project), and MCyT (J.L.M. and P.O). We also thank the $\Psi_k$ network and CEPBA for funding collaborative visits.

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*Electronic address: mbr@mic.dtu.dk

8. We employ the siesta package (Ref. 9) extended to the nonequilibrium situation by the TRANSIESTA method (Ref. 10).
15. The force is less than 0.02 nN on all wire atoms.
17. Terms which take into account incompleteness and nonorthogonality are included in praxis, see P. Ordejon, E. Artacho, and J. M. Soler, Phys. Rev. B **53**, R10 441 (1996).

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