Fundamental scaling properties of electro-mechanical switches

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Abstract. We discuss the fundamental processes including electron conduction and adhesion of metallic contacts pertaining to the scaling of the performance metrics of nano-electro-mechanical switches. In particular, we show that under most circumstances, the switching energy is governed by the force that is needed in order to break the electrical contact when opening the switch. For an optimally designed parallel plate capacitor switch, the energy consumption does not depend on the actuation voltage. However, stray capacitances degrade the energy efficiency if a high operating voltage is chosen. The limit is of the order of 1 V for an aggressively scaled Si device, for which an overall switching energy of the order of 150 eV, a footprint area of 2500 nm² and a switching time of 200 ps are predicted. The scaling analysis also stipulates that materials with a low free electron density and high effective mass should be used for the electrical contact, which is counter-intuitive, as such materials are known to be poor conductors on the macroscopic scale.

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1. Introduction

Nano-electro-mechanical (NEM) switches and relays have attracted increasing attention for their abrupt switching characteristics, absence of leakage and potentially lower energy consumption compared to complementary metal oxide semiconductor (CMOS) field effect transistor (FET) devices. State-of-the-art microelectronic systems are limited in their power efficiency by their sub-threshold characteristic. NEM switches, on the other hand, are limited by a fundamentally different mechanism as they make-and-break a current conducting path via a mechanical motion resulting in abrupt turn on–off characteristics.

Different approaches have been used to model the basic physics of the forces and energies involved with the goal of designing energy-efficient NEM switches, increasing the reliability and understanding the fundamental limits of this technology. Considering only the closing of the switch, simple models are obtained for estimating the switching time for a given actuation mechanism. These models do not account for contact adhesion and correspondingly low switching energies are predicted [1–5]. A release condition based on balancing the adhesion energy in the contact against the stored elastic energy in the switch has been introduced in [6, 7]. The energy criterion has been used to predict the ultimate scaling limits for an NEM switch, in circuit optimizations and for comparisons to CMOS technology [8, 9]. The criterion is applicable in the limit of a very small actuation stroke which has to be of the order of the range of interaction, typically 1 nm for a metal contact. In all other cases the switch needs to be designed from the point of view of providing a sufficient force to overcome the adhesive forces in order to physically open the electrical contact. Therefore, it is more appropriate to apply a force criterion, namely the restoring spring force must be larger than the adhesion force in the closed contact position, a fact that is well known [10, 11], yet its implication for the minimal switching energy has not been investigated.

Macroscopic approaches based on well-known contact models and yielding theory [12] have been used to assess the forces and resistances in metallic asperity contacts. The models have been extended to include multiple asperity contacts applying statistical [12, 13] and fractal surface models [14]. In this paper, we are considering electrical contacts approaching atomic dimensions. As will be shown later, a small contact area is a prerequisite for achieving energy-efficient switching which is competitive with future advanced CMOS technology. At this scale, the electrical contact resistance is governed by quantum confinement effects [15] and the yielding mechanics are distinctively different from the macroscopic world as has been first
pointed out by Landman et al [16] based on molecular dynamics simulations. Experimental studies of Au asperity contacts revealed the quantum nature of the electrical conductance. Furthermore, it was shown that the adhesive forces, of the order of nN per active conduction channel, correlate with discrete jumps of the electrical contact resistance [17, 18], which was interpreted in terms of spontaneous atomic rearrangements in the constriction as predicted by simulations.

In this paper, we give a comprehensive discussion of the physics governing the scaling of the energy consumption, operating voltage, switching time and areal footprint of electrostatically actuated mechanical switches under optimal energy conditions. Simple physical abstractions are used to arrive at analytical descriptions of the fundamental limiting processes, in particular also for the metallic adhesion interaction of the electrical contact which performs the switching function. The paper is organized as follows. The conduction properties and adhesion physics of nm scale metallic asperities are discussed in sections 2 and 3. In section 4 we derive operating conditions yielding optimum energy efficiency for a parallel plate capacitor actuator. The results are applied to an Si-cantilever implementation of the switch in section 5 giving insight into the scaling of the propagation delay and geometrical factors of the switch. Finally, the implications of the scaling analysis are discussed in section 6.

2. The electrical switch

Here we are concerned with the simple electrical on–off switching function which forms the basis of any binary logic circuit. Assuming a state-of-the-art processor architecture, the requirements on the switch can be abstracted in terms of an on resistance, \( R_{\text{on}} \sim 2 \text{k}\Omega \), in the closed state and an on–off ratio of less than \( \frac{R_{\text{on}}}{R_{\text{off}}} \sim 10^{-2} - 10^{-4} \) in order to keep leakage currents and power consumption within reasonable limits (larger on–off ratios are tolerated in high performance logic and lower ratios apply for low-power logic). A distinct advantage of the mechanical switch is the fact that the conduction path is physically broken in the open state yielding a virtually infinite off-resistance. Thus power consumption due to leakage currents is negligible. The on-resistance, on the other hand, is determined by the physical size of the electrical contact. The contact should have sufficient area in order to achieve a low value for \( R_{\text{on}} \sim 2 \text{k}\Omega \); however, it should be as small as possible in order to minimize energy losses due to adhesion.

Let us consider a mechanically actuated device which can open or close a metallic junction. The metallic junction should be of nm dimensions in order to minimize hysteresis loss, see section 3. Therefore, we assume that the mechanical switch operates on a single asperity contact, as shown in figure 1(a). In the open state, inset I, the two asperities are physically separated and electrons cannot pass through the gap between them. There will be a small attractive force acting on the asperities due to long-range electro-static and van der Waals forces. When the asperities are brought together within angstrom distance, the conduction electron wave functions substantially overlap, inset II. As a consequence, electron tunneling sets in, thereby gradually decreasing the off-resistance as the switch moves toward the closed position. More importantly, the asperities are pulled in by strong metallic adhesion forces originating from the exchange-correlation interaction in the overlapping electron gas in the apex region [19, 20]. In the final closed position, inset III, the adhesive forces are balanced by corresponding repulsive interactions originating from the kinetic energy of the dense electron gas and atomic hard core...
Figure 1. (a) Schematic diagram of a metal asperity contact in the open state (I), an intermediate state (II) where electron tunneling and strong adhesion interactions set in, and the final closed state (III). (b) Ballistic conductance model of the asperity contact. Because of the radial confinement of the contact, current carrying states, termed conduction channels, are quantized and the contact resistance is given by $R_c \approx \frac{\hbar}{2e^2 N} \approx \frac{12.9}{N}$, where $N$ is the number of conduction channels in the narrowest constriction of the contact. (c) Energy diagram of the metal contact. Far from the constriction, the conduction band consists of a virtual continuum of parabolic electron states up to the Fermi energy $E_F$. The quasi-continuum breaks up into discrete states in the constriction.

repulsion. The tunneling barrier has collapsed at this point and electrons can pass freely between the two asperities.

We assume that the dimension of the constriction in the hour-glass-like contact is small in comparison to the electron mean free path, i.e. less than 10 nm in radius. The constriction then
acts like a ballistic channel connecting two electron reservoirs which are in thermal equilibrium. The electron wave functions are confined in x and y in the asperity contact leading to a discrete quantization of the electronic states, termed conduction channels, see figure 1(b). An observer will then measure an electrical resistance between the two electron reservoirs which is given by the well-known Landauer– Büttiker equation [21]

\[ R_c = \frac{h}{2e^2 \sum_{i=1}^{N} T_i}, \]  

where \( h/(2e^2) \approx 12.9 \, \text{kΩ} \) is the quantum resistance and \( T_i \leq 1 \) is the transmission coefficient for the conduction channel \( i \) and \( N \) is the number of channels in the constriction. In our case we may set \( T_i = 1 \) since there is no transmission barrier and scattering in the constriction. Therefore, one concludes that six conduction channels are sufficient to reach the 2 kΩ target for the on-resistance of the switch.

The number of channels in the constriction depends on the radius \( R \) of the constriction. Consider a free electron gas of density \( n_e \) described by the Hamiltonian

\[ \mathcal{H} = \frac{p^2}{2m^*} + V(\vec{r}), \]  

where \( m^* \) denotes the effective mass of the electrons. For the sake of simplicity, we neglect tunneling and set \( V(\vec{r}) = \infty \) in the vacuum and \( V(\vec{r}) = 0 \) inside the metal. Far from the constriction, the conduction band is composed of a virtual continuum of parabolic electron states up to the Fermi energy \( E_F = \frac{h^2}{2m^*} \left( \frac{3\pi^2 n_e}{2} \right)^{2/3} \), see figure 1(c). The quasi-continuum of states breaks up into discrete states in the constriction. We assume cylindrical symmetry and also assume that the cross-section of the constriction varies slowly along the z-axis, which allows us to adopt an adiabatic approximation for calculating the electronic states. Accordingly, we write \( p^2 = \hbar^2 (\partial^2/\partial z^2 + \Delta_{r,\Phi}) \), where \( \Delta_{r,\Phi} \) denotes the two-dimensional Laplace operator in the cylinder coordinates \( r \) and \( \Phi \). The electron wave functions corresponding to the energy eigenstates can be written in terms of a product of a plane wave traveling along the z-axis and a radial wave function, i.e.

\[ \Psi(z, r, \Phi) = e^{ik_z z} \times \Psi(r, \Phi). \]  

The energy of the electron states is then \( E = \frac{\hbar^2 k_z^2}{2m^*} + E_\perp \), where \( E_\perp \) is the eigenvalue of the radial wave function equation, namely

\[ E_\perp \Psi(r, \Phi) = \frac{\hbar^2}{2m^*} \Delta_{r,\Phi} \Psi(r, \Phi). \]  

Each eigenstate of equation (4) corresponds to one conduction channel with a parabolic dispersion in \( k_z \) and an energy offset \( E_\perp \), see figure 1(c). The radial eigenstates are given by

\[ \Psi(r, \Phi) = J^m(\rho) e^{\pm im\Phi} \]  

with

\[ \rho = r \sqrt{2E_\perp m^*} \bigg/ \hbar, \]  

where \( J^m(\rho) \) denotes the Bessel function of order \( m \). The boundary condition \( \Psi(R, \Phi) = 0 \) yields the quantization of the eigenvalues of the radial energy \( E_\perp \),

\[ E^*_k = \frac{1}{2} \frac{\hbar^2}{m_e a_0^2} \frac{m_e a_0^2}{m^* R^2} \rho^2_k, \]  

where \( a_0 \) is the Bohr radius and \( m_e \) is the electron mass.
where $\rho_k^m$ denotes the $k$th zero of the Bessel function of order $m$, $\frac{k^2}{m\omega_0^2} = E_R \simeq 13.6$ eV is the Rydberg energy and $m_e$ and $a_0 \simeq 0.529 \text{Å}$ denote the electron mass and Bohr radius, respectively. The zeros of the Bessel function are approximately given by $\rho_k^m \simeq \pi (k + \frac{m}{2} - \frac{1}{4})$ and the energy levels corresponding to $\rho_1^M \simeq \rho_2^{M-2} \simeq \rho_3^{M-4} \simeq \rho_k^{M-2(k-1)} \simeq \rho_{M \text{ mod } 2}^{M-2} \simeq \frac{\pi}{2} (M + \frac{3}{2})$ ($\div 2$ denotes the integer division by 2 and mod 2 is the remainder of the integer division) are loosely degenerate and given by

$$E_M = E_R \frac{m_e a_0^2 \pi^2}{m^* R^2} \left( M + \frac{3}{2} \right)^2.$$  (8)

Note that $M$ is not a real quantum number but rather an index for the group of eigenstates corresponding to $E_M$. Observing that energy levels for $m > 0$ are two-fold degenerate because of the $e^{\pm im\phi}$ term in the wave function, we find that there are $M + 1$ states for a given $E_M$, and correspondingly, the total number of states with energy less than or equal to $E_M$ is

$$N_M = \sum_{M'=0}^{M} (M' + 1) = \frac{(M + 1)(M + 2)}{2}.$$  (9)

Only those states actively participate in electron conduction and thus form a conduction channel for which $E_M$ is less than the Fermi energy, which yields a condition for the minimum radius of the constriction

$$R_M > a_0 \frac{\pi}{2} \left( M + \frac{3}{2} \right) \left( \frac{E_R}{m_e} \right)^{1/2} \left( \frac{m^*}{E_F} \right)^{1/3} \left( M + \frac{3}{2} \right)^{1/3} \left( \frac{2}{n_e^{1/3}} \right).$$  (10)

For our switch we require that at least $N_M = 6$ channels are active. Therefore the minimum $M$ is 2 and assuming a Fermi energy of $E_F \simeq 5$ eV for a good metal, the minimum radius is $R \simeq 0.48$ nm.

3. Free electron model of the contact force

A minimum force has to be applied when opening the electrical contact in order to overcome the cohesive forces in the asperity contact. We model the metallic interaction using a jellium model for the background charge from the atoms and a free electron approximation for the conduction electrons. The free energy of the system can be written as [22]

$$\Omega = \omega V + \sigma S - \frac{2}{3} \frac{E_F}{\lambda_F} L + \delta \Omega,$$  (11)

where $\omega = -\frac{2}{15\pi^2} E_F k_F^2$ is the macroscopic free energy density, $V$ is the volume of the system, $\sigma = \frac{1}{16\pi} E_F k_F^2$ is the macroscopic surface free energy and $S$ is the surface area of the system. The remaining two terms are quantum corrections due to the discrete nature of the transverse states in the constriction where $L$ denotes the length of the constriction. Assuming ideal plasticity, the volume of the system remains unchanged during opening of the contact and one obtains for the tensile contact force

$$F = -\sigma \frac{\partial S}{\partial L} + \frac{2}{3} \frac{E_F}{\lambda_F} + \delta F.$$  (12)

The effect of the quantum correction is that the tensile force is reduced with respect to the macroscopic surface tension force by a constant value $\frac{2}{3} \frac{E_F}{\lambda_F}$ where $E_F$ and $\lambda_F = \frac{2\pi}{k_F}$, respectively,
denote the Fermi energy and the Fermi wavelength of the electron gas. The additional fluctuating quantum term \( \delta F = \frac{\delta F_0}{\lambda_F} \) can be positive or negative and the magnitude is of the order of 0.25 \( \times \frac{E_F}{\lambda_F} \).

Yielding of nanometer scale metallic asperities proceeds qualitatively in a different way than in macroscopic objects because dislocations cannot form for energetic reasons [23]. Molecular dynamics simulations by Landman et al [16] showed that plastic yielding in nanometer-sized asperity contacts involves structural transformations between ordered and disordered states of a few atomic layers in the constriction. In each transformation the cross-section \( A_c \) of the constriction shrinks when one atomic layer is added during the elongation of the asperity contact. Based on the modeling results, one may approximate the evolution of the shape of the asperity contact by considering a cylindrical transformation zone consisting of \( n \) atomic layers which is attached to rigid supports at both end surfaces. Since the mass is conserved during elongation one finds that \( n(d_0 A_c) = A_c \Delta L \), where \( d_0 \) denotes the lattice spacing. Integration of the mass balance equation yields

\[
A_c(L) = A_c(L_0) e^{\pi(L_0 - L)}
\]

(13)

with \( \kappa = \frac{1}{n d_0} \). The cross-section of the neck decreases exponentially as the asperity contact is elongated as has been observed experimentally in Au contacts with \( \kappa \approx 1 \text{ nm}^{-1} \) [18, 23].

In an elongation step \( \Delta L \) the surface area of the contact increases by an amount \( \Delta S = 2 \pi \Delta L (R_c + \frac{1}{\kappa} \frac{\Delta R_c}{\Delta L}) \), where \( R_c = \left( \frac{A_c}{\pi} \right)^{1/2} \) is the radius of the constriction. The first term accounts for the temporary elongation of the cylindrical transformation zone whereas the second term accounts for the shrinking of the radius. Invoking equation (13) we find that

\[
\frac{\Delta S}{\Delta L} = \pi R_c,
\]

(14)
yielding a tensile contact force of

\[
F = -\pi \sigma R_c + \frac{2}{3} \frac{E_F}{\lambda_F} + \delta F.
\]

(15)

Expressing \( E_F \) and \( k_F \) in terms of the free electron density, one finds that \( \sigma = \frac{3^{4/3} \pi^{5/3}}{32} \frac{E_R}{a_0} \frac{m}{m^*} (a_0^3 n_e)^{4/3} \) and \( \frac{E_F}{\lambda_F} = \frac{3}{2} \frac{E_R}{a_0} \frac{m}{m^*} a_0^3 n_e \). Substituting equation (10) for \( R_c \), we find for the tensile force of the contact

\[
F = \pi \left(\frac{3 \pi^2}{32} \left( M + \frac{3}{2} \right) - 1 \right) \frac{E_R}{a_0} \frac{m_e}{m^*} a_0^3 n_e + \delta F,
\]

(16)

where the number of conduction channels is given by equation (9). For a good metal one has \( E_F \approx 5 \text{ eV} \) and \( m^* \approx m_e \), which corresponds to an electron density of \( a_0^3 n_e \approx 0.01 \), and we obtain a tensile contact force of \( F \approx 1.6 \text{ nN} \times (M + \frac{1}{2}) \) in agreement with experimental results obtained from studying Au contacts [17, 18]. Accordingly, the minimum force required for breaking an asperity contact with six conduction channels, corresponding to \( M = 2 \), is of the order of 5 nN.

According to equation (16), the adhesive contact force scales linearly with the free electron density and inversely with the effective mass for a given contact resistance. This is an interesting result as it suggests that poor conductors on the macroscopic scale are actually preferred as contact materials for a nano-scale switch for which the adhesion force is a critical factor in terms of the overall energy efficiency, see below. From this perspective, graphitic materials are particularly attractive because of the high effective mass and low effective electron density.
Figure 2. (a) Schematic diagram of a spring loaded parallel plate capacitor actuator. The initial position of the capacitor plate with respect to a ground plane is $d_0$ when there is no voltage applied. By closing the switch $S_1$, the capacitor is connected to a voltage source $U$ causing the plate to move toward the ground plane. The motion comes to a stop at a distance $d_c$ when the contact is closed. (b) Cantilever implementation of a mechanical switch of length $l$, width $w$ and thickness $t$. The length and width can also be expressed in terms of the lever area $A = l \times w$ and an aspect ratio $\beta = \frac{l}{w}$. The contact closes at a distance $d_c = \frac{1}{2} d_0$ which minimizes the switching energy for $d_0$ greater than approximately $4 \times \lambda$.

which are associated with the $\pi$-bands. Of course, other interactions such as van der Waals and short range bonding interactions need to be considered as well. In general, however, van der Waals forces are approximately two orders of magnitude weaker than electronic exchange forces and short-range bonding forces should only play a role if chemically active dangling bonds are involved.

4. Energy scaling

The metallic asperity contact is opened and closed by means of an electrostatic actuator as depicted in figure 2. It consists of a parallel plate capacitor with an area $A$ per plate and the actuator plate is attached to a spring $k$. The capacitor plates are at a distance $d_0$ with no potential applied which corresponds to the open position of the switch. To close the switch, the actuator plate is connected to a battery $U$ by means of a fast external switch $S_1$ causing the plate to move to the closed contact position $d_c$ due to electrostatic forces. We assume, of course, that the electrostatic force is sufficient to overcome the restoring spring force $F_r = k(d_0 - d_c)$.
To complete the actuation, the battery must deliver an energy $E_{\text{act}} = \int U I \, dt = \int U \, dQ = C(d_c)U^2$. The energy is composed of two terms $E_{\text{act}} = E_1 + E_2$ corresponding to two distinct steps. In a first step, the capacitor is rapidly charged at the initial position $d_0$ causing an energy drain $E_1 = C(d_0)U^2$ from the battery. Half of this energy is stored in the electric field and half of it is dissipated in the electrical circuit. In the second step the capacitor plate is accelerated toward the counter-electrode where it comes to a stop at $d_c$ when the switch is closed. The corresponding energy $E_2 = \int_{\text{open}}^{\text{close}} U I \, dt = (C(d_c) - C(d_0))U^2$ is again half split between electrical field energy stored in the capacitor and mechanical energy involving the energy stored in the spring and kinetic energy of the moving capacitor plate.

The 50% fraction of the energy $E_2$ which is available for actuation is most efficiently converted into a spring deflection in a ballistic mode. Here, damping of the spring motion is assumed to be negligible and all the electrical energy surplus which is not consumed as potential energy in the spring is converted into kinetic energy. Therefore, the requirement on the actuation voltage can be phrased in terms of an energy condition, namely $1/2 E_2(d) = 1/2 C(d_0)((d_0/d_c)^2 - 1)U^2$ must be greater than or equal to the potential energy of the spring $E_{\text{spring}}(d) = 1/2 kd_c^2(1 - (d/d_c)^2)$ at any position $d$ along the actuation path, namely $d_0 \geq d \geq d_c$, yielding

$$U^2_{\text{ballistic}} \geq \frac{kd_0^2}{C(d_0)} \left\{ \begin{array}{ll} \frac{d}{d_0} \left( 1 - \frac{d}{d_0} \right) & \text{if } d_c \geq \frac{d_0}{2}, \\ \frac{1}{4} & \text{if } d_c < \frac{d_0}{2}. \end{array} \right. \quad (17)$$

In a more conservative quasi-static mode, the kinetic energy is neglected and the requirement for the actuation voltage is now phrased in terms of a static force condition, namely, the capacitive force $F_{\text{cap}}(d) = \frac{1}{2} C(d_0) \left( \frac{d_0}{d_c} \right)^2 U^2$ must be greater than or equal to the restoring spring force $F_{\text{spring}} = k(d_0 - d)$ at any position $d$ along the actuation path yielding

$$U^2_{\text{quasi-static}} \geq \frac{kd_0^2}{C(d_0)} \left\{ \begin{array}{ll} \left( \frac{d}{d_0} \right)^2 \left( 1 - \frac{d}{d_0} \right) & \text{if } d_c \geq \frac{d_0}{2}, \\ \left( \frac{2}{3} \right)^3 & \text{if } d_c < \frac{d_0}{2}. \end{array} \right. \quad (18)$$

Figure 3(a) shows the minimum actuation voltage $U^2_{\text{min}}$ as a function of $d_c/d_0$. $U^2_{\text{min}}$ reaches a maximum value of 0.25 and $(2/3)^3 \approx 0.3$ (in units of $kd_0^2/C(d_0)$) at a critical normalized contact distance $d_c/d_0$ of 0.5 and 2/3 for the ballistic and quasi-static actuation mode, respectively. The maximum actuation voltage still applies for $d_c/d_0$ smaller than the respective critical values as it represents a barrier that needs to be overcome in a snap-in actuation mode. Note that actuation in the plateau regime results in an energy and force surplus at $d_c$ which needs to be absorbed by the nanometer scale electrical contact structure. On the other hand, ballistic actuation in the regime $d_c/d_0 > 0.5$ is statically unstable as the capacitive pull-in force is less than the retracting spring force. This force in-balance would have to be compensated for by adhesive contact forces. The most gentle and still statically stable actuation is therefore obtained for $d_c/d_0 = 0.5$ using a ballistic actuation voltage of $U^2 = \frac{kd_0^2}{4C(d_0)}$.

As we have discussed above, the formation of an electrical contact involves adhesive interactions which need to be overcome when the contact is opened. The corresponding energy and forces must be provided by the spring. The ballistic condition for overcoming the adhesion
Figure 3. (a) Minimum voltage $U$ which is required to move a spring loaded capacitor plate from an initial position $d_0$ to a final position $d_c$ for quasi-static and ballistic actuation. (b) Actuation energy which is required for moving a spring loaded capacitor plate from an initial position $d_0$ to a final position $d_c$ under the condition that the energy stored in the spring is sufficient to overcome the adhesion interaction $W_{ad}$ which falls off over a distance $\lambda$. (c) Actuation energy as a function of $d_0/\lambda$ for a final position $d_c$ yielding the minimum energy.

Energy can be phrased as $W_{ad} + W_{int}(x) \leq \frac{1}{2} k ((d_0 - d_c)^2 - (d_0 - d_c - x)^2) = k (d_0 - d_c)x + \frac{1}{2} x^2$ for any value of $x$ in the interval $(d_0 - d_c) > x > 0$. Here, $W_{ad}$ is the total work of adhesion involved in breaking the asperity contact and $W_{int}(x)$ is the corresponding interaction potential with $W_{int}(0) = -W_{ad}$ and $W_{int}(\infty) = 0$. Approximating the interaction energy by a simple linear law $W_{int}(x) = -W_{ad}(1 - \frac{x}{\lambda})$, where $\lambda$ denotes the range of interaction, we find a condition for the minimum value of the spring constant

$$k \geq \frac{W_{ad}}{\lambda d_0} \frac{1}{1 - \frac{d_c}{d_0} - \frac{1}{2} \frac{d_c}{d_0}}. \quad (19)$$

Substituting the above condition into equations (17) and (18) and using $E_{act} = C(d_c)U^2 = \frac{d_c}{d_0} C(d_0)U^2$, we find that

$$E_{act} \geq W_{ad} d_0 \lambda \left\{ \begin{array}{ll}
\frac{1 - \frac{d_c}{d_0}}{1 - \frac{d_c}{d_0} - \frac{1}{2} \frac{d_c}{d_0}} & \text{if } d_c \geq \frac{d_0}{2}, \\
\frac{1}{4} \frac{d_c}{d_0} \left(1 - \frac{d_c}{d_0} - \frac{1}{2} \frac{d_c}{d_0}\right) & \text{if } d_c < \frac{d_0}{2}
\end{array} \right. \quad (20)$$

for ballistic actuation and

$$E_{act} \geq W_{ad} d_0 \lambda \left\{ \begin{array}{ll}
\frac{2 d_c}{d_0} \frac{1 - \frac{d_c}{d_0}}{1 - \frac{d_c}{d_0} - \frac{1}{2} \frac{d_c}{d_0}} & \text{if } d_c \geq \frac{2d_0}{3}, \\
\left(\frac{2}{3}\right)^3 \frac{d_c}{d_0} \left(1 - \frac{d_c}{d_0} - \frac{1}{2} \frac{d_c}{d_0}\right) & \text{if } d_c < \frac{2d_0}{3}
\end{array} \right. \quad (21)$$

for quasi-static actuation, respectively. The energy minimum is obtained at an actuation distance

$$d_c = \frac{1}{2} d_0 - \frac{1}{4} \lambda. \quad (22)$$
The actuation distance yielding minimum actuation energy shifts to lower values when the $d_0$ becomes comparable to $\lambda$, see figure 3(b). However, there is a lower bound for $d_0 = \frac{3}{2} \lambda$ corresponding to $d_c = \frac{1}{3} d_0$, which is given by the condition that the actuator stroke $d_0 - d_c$ must be greater than the range of interaction $\lambda$. Substituting equation (22) into equations (20) and (21), we obtain the absolute minimum of the energy which is required for electrostatic switch actuation as a function of the width of the gap $d_0$ between the capacitor planes, see figure 3(c):

$$\min E_{\text{act}} = W_{\text{ad}} \frac{d_0}{\lambda} \left(1 - \frac{1}{2} \frac{\lambda}{d_0}\right)^2 \times \begin{cases} 1 & \text{ballistic actuation} \\ 4 \left(\frac{2}{3}\right)^3 & \text{quasi-static actuation} \end{cases}$$

$$\approx 6.25 \text{ eV} \times \left(1 - \frac{1}{2} \frac{\lambda}{d_0}\right)^2 \times \begin{cases} \frac{1}{1.19} \times \frac{W_{\text{ad}}}{\lambda} \text{ nN}^{-1} \times d_0 \text{ nm}^{-1}. \end{cases} \quad (23)$$

The actuation energy levels off at a minimum value of the order of $4 \times W_{\text{ad}}$ as published in [7]. However, this minimum energy is only obtained at a very small gap distance $d_0 = \frac{3}{2} \lambda$. The actuation energy increases with increasing gap distance and for $d_0 > 4 \times \lambda$ the actuation energy scales linearly with $d_0$. The scale factor is given by the ratio $\frac{W_{\text{ad}}}{\lambda}$ which can be interpreted as an effective adhesion force $F_{\text{ad}}$ which needs to be overcome by the spring force $k(d_0 - d_c)$ at contact. One also sees that ballistic actuation is only marginally superior to quasi-static actuation by a factor of $4 \left(\frac{2}{3}\right)^3 \approx 1.2$ both in terms of the minimum switching energy and switching voltage (see equations (17) and (18)). We have argued above that from the point of view of minimizing the contact load, the contact distance should be chosen at half the gap distance, namely $d_c = \frac{1}{2} d_0$ is optimum. This optimum contact distance also minimizes the actuation energy for a gap width of $d_0 > 4 \times \lambda$ and even for $d_0 < 4 \times \lambda$ the actuation energy is less than 30% from the absolute minimum value, see figure 3(b).

5. Geometrical scaling

In a next step we consider a cantilever style implementation of the switch as depicted in figure 2(b). We assume that the switch is operated under optimum energy conditions in a ballistic mode and further assume that the gap $d_0$ is larger than $4 \times \lambda$, and correspondingly, the contact distance is $d_c = \frac{1}{3} d_0$. Since $W_{\text{ad}}$ and $\lambda$ are given properties of the contact, the minimum spring constant of the cantilever beam is fixed by equation (19), $k = \frac{2 W_{\text{ad}}}{\lambda d_0}$. We also assume that the actuation voltage $U$ is fixed by technology requirements, which in turn sets a lower limit on the electrical capacitance of the cantilever structure. We still have the choice to select an additional parameter from the geometrical constants $w, l, t$, of the cantilever. Here, we select the beam thickness $t$ as a free parameter. We furthermore express the width and length of the cantilever in terms of the footprint area $A = w \times l$ and an aspect ratio $\beta = \frac{l}{w}$, namely $l = \beta^{1/2} A^{1/2}$ and $w = \beta^{-1/2} A^{1/2}$. Substituting $k = \frac{2 W_{\text{ad}}}{\lambda d_0}$ into equation (17), we obtain that

$$C(d_0) = \frac{1}{2} W_{\text{ad}} \frac{d_0}{\lambda} \frac{1}{U^2} = \frac{1}{2} \min E_{\text{act}} \approx 6.25 \text{ aF} \times \frac{W_{\text{ad}}}{\lambda} \text{ nN}^{-1} \times \frac{1}{U^2} \text{ V}^2 \times d_0 \text{ nm}^{-1}. \quad (24)$$

New Journal of Physics 14 (2012) 123007 (http://www.njp.org/)
The capacitance of a parallel plate structure is given by $C(d_0) = \varepsilon_0 A/d_0$ where $\varepsilon_0 = 8.85 \times 10^{-12}$ N V$^{-2}$ is the vacuum permittivity. We then obtain a first scaling law for the cantilever footprint:

$$A = \frac{1}{2} \frac{W_{ad}}{\varepsilon_0 U^2} d_0^2 \simeq 56.5 \times \frac{W_{ad}}{\lambda} \text{nN}^{-1} \times \frac{1}{U^2} \text{V}^2 \times d_0^2.$$

(25)

The spring constant of a cantilever beam of given dimension is $k = \frac{1}{4} E \frac{w}{t^3} = \frac{1}{4} \frac{E \pi}{\beta^2 A}$ [24], where $E$ denotes the elastic modulus. Substituting equation (25) for $A$ and using the minimum energy condition $k = \frac{2W_{ad}}{\lambda d_0}$ (see above), we find for the aspect ratio of the beam

$$\beta = \frac{(\varepsilon_0 E)^{1/2}}{2} \frac{U}{W_{ad}} \frac{t^{3/2}}{d_0^{1/2}} \simeq 4.71 \times 10^{-2} \times E^{1/2} \text{GPa}^{-1/2} \times \frac{1}{W_{ad}} \times \text{nN} \times \frac{1}{U} \times \frac{1}{V} \times \frac{t^{3/2}}{\text{nm}^{-3/2}} \times \frac{1}{d_0^{1/2}} \times \text{nm}^{1/2},$$

(26)

which defines the actual shape of the lever.

The propagation delay $\tau$ of the switch is defined as the time it takes from applying the potential $U$ by closing the external switch $S_1$ until the cantilever has reached the closed position $d_c$. For ballistic actuation with zero net force at $d_c$ the propagation delay is exactly $\frac{1}{4}$ of the oscillation period $T = \frac{2\pi}{\omega_0}$ of the fundamental bending mode of the cantilever. The fundamental mode frequency is given by $\omega_0 = 1.02 \times \frac{E}{\varepsilon_0} \left(\frac{\rho}{\lambda}\right)^{1/2} = 2.04 \times \left(\frac{\rho}{E}\right)^{1/2}$ [24], where $\rho$ denotes the density of the cantilever and $m = \rho A t$ is the mass of the cantilever. With $k = \frac{2W_{ad}}{\lambda d_0}$ and substituting equation (25) for $A$, we find that

$$\omega = 4.06 \times \left(\frac{\varepsilon_0}{\rho}\right)^{1/2} \frac{U}{t^{1/2}} \frac{1}{d_0^{1/2}} \simeq 3.84 \times 10^{11} \text{s}^{-1} \times \frac{1}{\rho^{1/2}} \left(\text{g cm}^{-3}\right)^{1/2} \times \frac{1}{U} \times \frac{1}{V} \times \frac{1}{t^{1/2}} \times \frac{1}{nm^{1/2}} \times \frac{1}{d_0^{1/2}} \times \text{nm}^{3/2},$$

(27)

and

$$\tau = \frac{1}{4} \frac{2\pi}{\omega_0} = 1.02 \times \left(\frac{\rho}{\varepsilon_0}\right)^{1/2} \frac{1}{U} \times t^{1/2} \times d_0^{3/2} \simeq 4.09 \text{ps} \times \rho^{1/2} \left(\text{g cm}^{-3}\right)^{-1/2} \times \frac{1}{U} \times V \times t^{1/2} \times \text{nm}^{-1/2} \times \text{d}_0^{3/2} \times \text{nm}^{-3/2}.$$

(28)

Interestingly, the propagation delay does not depend on the contact strength $\frac{W_{ad}}{t}$ and is just determined by the actuation voltage $U$, the gap width $d_0$, the lever thickness $t$ and the density $\rho$. For a real device one would like to minimize the propagation delay, which means that one would strive to minimize the cantilever thickness $t$. However, a small value of $t$ also means a small value for the aspect ratio $\beta$, see equation (26). For practical reasons we set $\beta = 1$ as a lower limit, which relates $t$ and $d_0$.

$$t_{\beta=1} = \frac{2^{2/3}}{\varepsilon_0^{1/3}} \frac{E^{1/3}}{U^{2/3}} \times \frac{W_{ad}}{\lambda}^{2/3} \times d_0^{1/3} \simeq 7.67 \text{nm} \times \frac{1}{U^{1/3}} \times \text{GPa}^{1/3} \times \left(\frac{W_{ad}}{\lambda}\right)^{2/3} \times \frac{1}{U^{2/3}} \times \text{nN}^{-2/3} \times \frac{1}{V^{2/3}} \times d_0^{1/3} \times \text{nm}^{-1/3}.$$

(29)
Substituting the above expression for $t$ into equation (28), we find for the $\beta = 1$ constrained minimum propagation delay
\[
\tau_{\beta=1} = 1.29 \frac{\rho^{1/2}}{\epsilon_0^{2/3} E^{1/6}} \left( \frac{w_{ad}}{\lambda} \right)^{1/3} U^{4/3} \approx 30.1 \text{ ps} \times \rho^{1/2} \left( \text{g cm}^{-3} \right)^{-1/2} \times \frac{1}{E^{1/6}} \text{GPa}^{1/6} \times \left( \frac{W_{ad}}{\lambda} \right)^{1/3} \text{nN}^{-1/3} \times \frac{1}{U^{4/3}} \text{V}^{4/3} \times d_0^{5/3} \text{nm}^{-5/3}.
\]

(30)

Note that the actuation voltage and the gap width are the most critical parameters for the propagation delay whereas the material parameters, in particular the elastic modulus, play a substantially less important role.

Capacitive charging of the interconnection wiring is another important contribution to the overall energy budget of NEM switch-based logic. We assume that the length of the wires roughly scales with the lateral dimensions of the switch. Accordingly, we write for the wire capacitance $C_w = \Gamma c A^{1/2}$ where the scale factor $\Gamma$ depends on the wiring topology of the logic and $c$ is the wire capacitance per unit length. With $E_w = C_w U^2$ and substituting equation (25) for $A$, we find that
\[
E_w = \frac{\Gamma}{\sqrt{2}} \epsilon_0^{1/2} U c d_0 \approx 47.0 \text{ eV} \times \Gamma \times \left( \frac{W_{ad}}{\lambda} \right)^{1/2} \text{nN}^{-1/2} \times \text{V}^{-1} \times c \text{ fF}^{-1} \text{ nm}^{-1} \times U^{1/2} \times \text{V} \times \text{nN}^{-1/2} \times \text{c fF} \times \text{nm}^{-1}.
\]

(31)

The total energy budget of an NEMS logic gate is thus given by $E_{\text{tot}} = E_{\text{act}} + E_w$. The condition $E_w(U_{co}) = E_{\text{act}}(U_{co})$ defines a crossover voltage
\[
U_{co} = \left( \frac{\sqrt{2} \epsilon_0^{1/2} W_{ad}}{\Gamma c} \right)^{1/2} \approx 0.133 V \times \frac{1}{\Gamma} \times \left( \frac{W_{ad}}{\lambda} \right)^{1/2} \text{nN}^{-1/2} \times \frac{1}{c} \text{ fF} \times \text{nm}^{-1}.
\]

(32)

If the actuation voltage $U$ is less than $U_{co}$, the total energy is dominated by the actuation energy of the switch, and conversely, if $U > U_{co}$ the total energy is dominated by the charging energy in the wires. With the above definition of $U_{co}$ we obtain for the total switching energy
\[
E_{\text{tot}} = \min E_{\text{act}} \left( 1 + \frac{U}{U_{co}} \right) = 6.25 \text{ eV} \times \left( 1 + \frac{U}{U_{co}} \right) \times \frac{W_{ad}}{\lambda} \text{nN}^{-1} \times d_0 \text{ nm}^{-1}.
\]

(33)

To discuss the implications of the scaling relations, let us consider an Si cantilever switch. Correspondingly, we have $E = 170 \text{ GPa}$ for a (110) cantilever orientation [25] and $\rho = 2.33 \text{ g cm}^{-3}$. We assume a value of $W_{ad} = 5 \text{ nN}$ for the adhesion force of the electrical contact which corresponds to the interaction expected for an asperity contact supporting six conduction channels yielding approximately $2 \text{k}$ contact resistance in the closed state. With these parameters we obtain from equation (25) for the footprint of the switch of $A \approx 280 \text{ nm}^2 \times \left( \frac{1}{32} \right) \text{V}^2 \times d_0^3 \text{ nm}^{-2}$, see figure 4(a), and from equation (26) one calculates an aspect ratio of $\beta = \frac{1}{w} \approx 0.12 \times U \text{V}^{-1} \times t^{3/2} \text{ nm}^{-3/4} \times d_0^{1/2} \text{ nm}^{-1/2}$, see figure 4(b). The $\beta = 1$ constrained minimum propagation delay $\tau_{\beta=1} \approx 33 \text{ ps} \times \sqrt{\frac{1}{\mu_{\text{eff}}} \text{V}^{4/3} \times d_0^{5/3} \text{ nm}^{-5/3}}$, see equation (31), is plotted in figure 4(c).

The total energy is $E_{\text{tot}} = E_w + \min E_{\text{act}}$ where $\min E_{\text{act}} \approx 31 \text{ eV} \times d_0 \text{ nm}^{-1}$ is given by equation (23). In order to estimate the wiring energy we need to know $\Gamma$ and $c$ for an appropriate
Figure 4. Geometrical scaling for an Si cantilever style mechanical switch optimized with respect to minimum switching energy. An interaction strength $w_{ad} = 5 \text{nN}$ is assumed, which is a typical value for a metallic contact yielding an on-resistance of 2 kΩ. (a) Footprint $A = w \times l$ of the cantilever versus gap width $d_0$ for different actuation voltages as indicated in the figure ($w$ and $l$, respectively, denote the width and length of the cantilever, see figure 2). (b) The aspect ratio $\beta = \frac{l}{w}$ of the cantilever versus gap width $d_0$ for different values of the actuation voltage and lever thickness $t$ as indicated in the figure. (c) Propagation delay $\tau$ of the switch versus gap width $d_0$ for an aspect ratio of $\beta = 1$ and for different actuation voltages as indicated in the figure. (d) Switching energy versus gap width $d_0$ for an actuation voltage of 1 V (solid curve) and versus actuation voltage for a gap width $d_0 = 10 \text{nm}$ (dashed curve). Note that the mechanical switching energy does not depend on the actuation voltage. However, interconnect capacitances may not be neglected above a crossover voltage of $U_{co} \simeq 1.5 \text{V}$ giving rise to a linear increase of the energy with $U > U_{co}$. Interconnect technology. Assuming a value of $\Gamma = 1$ and $c = 0.2 \text{fF} \mu \text{m}^{-1}$ as predicted for the metal 1 layer by the International Technology Roadmap for Semiconductors (ITRS) road map (www.itrs.net/Links/2011ITRS/2011tables/) one finds that $E_w \simeq 21 \text{eV} \times U^{-1} \times d_0 \text{nm}^{-1}$ and correspondingly the crossover voltage is $U_{co} \simeq 1.5 \text{V}$, see equations (32) and (33). We then find for the total energy of the switch $E_{tot} \simeq 31 \text{eV} \times (1 + \frac{U}{U_{co}}) \times d_0 \text{nm}^{-1}$, see figure 4(d). As can be seen from figure 4(d), there is no incentive in terms of overall energy efficiency for using an actuation voltage which is substantially less than $U_{co}$. In fact, the $\frac{1}{U^2}$ scaling of $A$ and the $\frac{1}{U^{4/3}}$
scaling for $\tau_{\beta=1}$ provide a strong push for using the maximum possible operating voltage for the NEM switch. Furthermore, the scaling equations show that the gap width $d_0$ is one of the most critical parameters which should be minimized. There is, however, a lower bound, namely $d_0 \geq \frac{3}{5} \lambda$, set by the range of the adhesive interaction in the asperity contact, as discussed at the end of section 4.

For an aggressive energy optimized switch design with $d_0 = 3\,\text{nm}$ and $U = 1\,\text{V}$, we obtain the following benchmarks: footprint: $A \simeq 2.5 \times 10^3 \,\text{nm}^2$; minimum propagation delay for an aspect ratio of $\beta = 1$: $\tau_{\beta=1} \simeq 200\,\text{ps}$; minimum switching energy: $E_{\text{tot}} = 155\,\text{eV}$. These numbers must be compared with the characteristics of a standard CMOS switch. According to the ITRS2011 road map for low-power logic, a current state-of-the-art low-power NMOSFET transistor is characterized by a specific source–drain resistance of $r_{\text{sd}} = 250\,\Omega\,\mu\text{m}$, a propagation delay of $\tau_{\text{CMOS}} = 1.15\,\text{ps}$, and a specific dynamic power indicator of $\text{dpi} = 0.44\,\text{fJ}\,\mu\text{m}^{-1} = 2.75 \times 10^3\,\text{eV}\,\mu\text{m}^{-1}$. The on-resistance of the transistor is $R_{\text{on}} = \frac{r_{\text{sd}}}{w_{\text{channel}}}$, where $w_{\text{channel}}$ denotes the width of the drain–source channel which is also approximately equal to the width of the transistor. Therefore, a transistor with an on-resistance of $R_{\text{on}} = 2\,\text{k}\Omega$ as considered for the mechanical switch must have a channel width of $w_{\text{channel}} = 125\,\text{nm}$. Correspondingly, we obtain for the dynamic power indicator $\text{DPI} = \text{dpi} \, w_{\text{channel}} = 350\,\text{eV}$. The DPI in essence denotes the energy for charging the gate capacitance. The overall switching energy is approximately three times larger due to parasitic capacitance effects. Therefore, the aggressively scaled mechanical switch offers approximately $6 \times$ superior energy efficiency. However, one must keep in mind that CMOS scaling will continue and DPI values of the order of $80\,\text{eV}$ are predicted to be state of the art by 2020. This implies that it will be very difficult for an Si-based mechanical switch design to compete with CMOS technology in terms of power consumption in the future. The footprint area of the mechanical switch is competitive, however, since the channel width will only shrink marginally in future devices for a given value of $R_{\text{on}}$. On the other side, the mechanical switch falls dramatically short in terms of the propagation delay which is two orders of magnitude larger than that of a comparable CMOS transistor. To improve the propagation delay, one has to reduce the actuator thickness and the gap width, see equation (28). The actuator thickness is ultimately limited by atomic dimensions to $t_{\text{min}} \simeq 0.3\,\text{nm}$ and electron tunneling limits the minimum gap width to $\simeq 1\,\text{nm}$. For a graphene sheet actuator with $\rho \simeq 1.2\,\text{g}\,\text{cm}^{-3}$ one then estimates that a propagation delay of the order of $3\,\text{ps}$ could be achieved, in principle, with an actuation voltage of $1\,\text{V}$.

It is clear that the scale factors in the geometric scaling equations (25)–(33) depend on the actual implementation of the switch. For example, a double-clamped structure has a much higher spring constant $k \simeq 4E_0 \frac{t^3}{B^2} \lambda^4$ than the single-clamped beam and correspondingly the pre-factor in equation (26) which defines the aspect ratio $\beta$ changes from $\frac{1}{2}$ to 2. Similarly, the resonance frequency is higher, namely $\omega \simeq 3.25 \left( \frac{L}{m} \right)^{1/2}$, and correspondingly the pre-factor in equation (28) which defines the propagation delay $\tau$ changes from 1.02 to 0.64. Therefore, different designs will yield different numerical factors in the scaling equations resulting in different trade-offs between the geometrical constants. However, the switching energy is fundamentally limited by equation (23). No matter what design is chosen, this limit will never be surpassed. Finally, we neglected that the fixed end of the cantilever does not move which in essence reduces the effective capacitance in the switch by approximately 50%, an effect which can be mitigated by a more complex actuator design [26]. As a result, the scaling equations are on the optimistic side. In particular, the minimum footprint will be larger by approximately a factor of 2 giving rise to an additional stray capacitance of the order of $60\,\text{aF}\,\text{V}^{-2}\,\text{nm}^{-1} \times \frac{1}{\tau^2} \times d_0$, see equation (24).
As a result a parasitic energy of the order of $E_{\text{parasitic}} \simeq 0.5 \times \min E_{\text{act}}$ must be added to the total switching energy in equation (24), namely $E_{\text{tot}} = \min E_{\text{act}} + E_{\text{parasitic}} + E_w$.

6. Summary and conclusions

The most important factor determining the overall energy efficiency of an electrostatically actuated mechanical switch is the adhesive interaction of the metal contact which performs the electrical switching function. More specifically, we show that for an energy optimized design the switching energy scales as the overall actuation stroke times an effective contact force $\frac{W_{\text{ad}}}{\lambda}$ where $W_{\text{ad}}$ is the overall adhesive energy of the contact and $\lambda$ denotes the range of interaction, namely the inverse measure of how rapidly the interaction falls off when the contact is opened. An actuation stroke of one half of the width of the gap between the capacitive plates forming the electro-mechanical actuator is optimum in two ways: firstly, it minimizes the electrical energy in the system, and secondly, it also minimizes the mechanical load on the contact in the closed position. The latter is important in order to preserve the nanometer scale of the metal contact. Therefore, the width of the capacitor gap should be minimized for high energy efficiency but it cannot be made smaller than $\frac{3}{2} \lambda$ since otherwise the switch would not open properly. In this limiting case, the overall switching energy approaches the value of $4 \times W_{\text{ad}}$ as has been derived previously in [7]. However, this limit is hardly ever achieved in a practical device implementation given the fact that $\lambda$ is of the order of 1 nm, typically.

In order to achieve the smallest possible contact force, one needs to minimize the area of the electrical contact. A lower bound is given by quantum confinement effects which set a limit for the electrical contact resistance of $\simeq 12.9 \text{k}\Omega$ divided by the number of active conduction channels. Therefore six channels, corresponding to a contact area of $\simeq 1 \text{nm}^2$, are sufficient to achieve an on-resistance of $\simeq 2 \text{k}\Omega$ as in a typical CMOS gate. Estimating the contact adhesion using a free electron model we obtain a contact force of $\simeq 1 \text{nN}$ per conduction channel in good agreement with experimental data obtained from the study of Au nano-asperities. More interestingly, the model also predicts that for a given contact resistance the contact force should scale as the free electron density and inversely as the effective electron mass. This suggests that rather than good metals, materials that are known to be poor conductors on the macroscopic scale should be used for the electrical contact in an energy optimized switch. In particular, one may expect that graphitic material is a promising candidate for the electrical contact because of the large effective mass and low effective electron density associated with the $\pi$-bands yielding a correspondingly weak coupling force between the graphitic layers.

The switching energy for an optimally designed electro-mechanical switch does not depend on the actuation voltage, nor on the specific design. Other important performance metrics such as the areal footprint or the propagation delay vary with the design specifics and they scale inversely with the actuation voltage to the power of 2 and $4/3$, respectively. This scaling provides a strong push to use the maximum possible operating voltage in order to achieve a high integration density and fast operating speed. Parasitic capacitances, e.g. due to interconnection wiring and implementation trade-offs, contribute to the overall energy equation and we estimate that this will become significant at voltage levels of the order of 1 V. For an aggressively designed Si cantilever switch, we estimate the overall switching energy to be of the order of 150 eV. This compares favorably with the DPI factor of 350 eV for a comparable state-of-the-art CMOS FET. However, the energy premium most likely will erode with further improvements of the CMOS technology, namely a DPI factor of 80 eV is predicted by the ITRS road map.
to be state of the art by 2020. The estimated footprint and propagation delay of the cantilever switch are 2500 nm$^2$ and 200 ps, respectively. While the footprint is competitive the propagation delay of the switch is off by approximately two orders of magnitude. The large propagation delay calls for a correspondingly low clock frequency. Therefore, to recover computational efficiency radically new designs of basic logic or arithmetic functions have been proposed [27, 28] which significantly reduce the cascading of Boolean operations and exploit the fact that the mechanical switch can drive a large number of switches concurrently (due to the overall slower operation). Nevertheless, it remains questionable whether mechanical gates will be competitive for replacing CMOS technology in conventional computing applications. However, because of the virtual absence of leakage in the open state they offer interesting options for energy critical applications with low duty cycle, e.g. remote event sensing in locations which are difficult to access. Also, the switch as such is a robust device which can withstand harsh environments in terms of temperature and radiation much better than CMOS devices. Finally, to improve the energy efficiency one may conceive schemes for the recovery of stored electrostatic energy and for minimizing charging losses. However, the adhesion hysteresis losses, of the order of 6 eV per conduction channel in a metal contact, cannot be recovered and thus fundamentally limit the energy efficiency even in otherwise perfectly adiabatic devices.

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New Journal of Physics 14 (2012) 123007 (http://www.njp.org/)