Fluidic Nanoelectronics and Brownian Dynamics

Marina Alexandra Lyshevski^{*} and Sergey Edward Lyshevski^{**}

*Microsystems and Nanotechnologies, Webster, NY 14580-4400, USA E.Lyshevski@rit.edu *Department of Electrical Engineering, Rochester Institute of Technology. Rochester, NY 14623, USA

ABSTRACT

We examine a novel synthetic fluidic molecular electronic module as well as emerging molecular electronics to be utilized in envisioned molecular integrated circuits (^MICs) and information processing platforms. The proposed multi-terminal module mimics neuron topology and organization using phenomena, effects and functionality observed in bioelectronics. Information processing and communication capabilities exhibited by biomolecules can be utilized by controlling electronic characteristics, folding as well as molecular transport. In a neuron, the electronic characteristics and folding change due to molecule binding/unbinding, while particles (molecules and ions) which propagate in the synaptic clefts, membrane channels and cytoplasm are analogous to the proposed synthetic activating and regulating information carriers. By prototyping and enhancing the functionality of a neuron, we study the controlled propagation of Brownian particles under the thermal, hydrodynamic and electromagnetic forces. The molecules are the activating and regulating information carriers in the fluidic cavity of the studied module. The analytical and numerical results are reported.

Keywords: molecular electronics, fluidic molecular module, molecular integrated circuits, Brownian dynamics

1. INTRODUCTION

New paradigms in molecular electronics and ^MICs have been emerged. Commercial high-yield high-performance molecular electronics is expected to mature by 2015 [1]. In general, molecular electronics can be classified as:

1. Organic/inorganic/hybrid; 2. Fluidic;

3. Biomolecular; 4. Integrated.

Information processing platforms, that include processors and memories, can be synthesized using synthetic neuronal hypercells (^{*}hypercells) within 3D topology, organizations and architectures [1]. Vertebrates possess superb bioelectronics. Therefore bioinformation processing platforms are of our interest. However, not only vertebrates, but single-cell bacteria (E. Coli, Salmonella typhimurium and other) possess superb 3D bioelectronics. We focus the efforts on the synthetic fluidic molecular electronics due to a limited knowledge on the baseline processes, phenomena, effects, functionality and engineering of bioelectronic Insufficient knowledge makes it virtually devices. impossible to comprehend and fully prototype biomolecular devices, not to mention systems, which may operate utilizing different phenomena and concepts as compared to the proposed to date molecular devices. However, the similarity of 3D topology and organization, as well as the use of molecules as *activating* and *regulating information carriers*. are of a great importance and particular interest. Synthetic organic and fluidic molecular electronics can be viewed as

evolutionary developments of biomolecular electronics which is a sound proving ground of the proposed fundamental, applied and technological developments.

We study the controlled Brownian dynamics of molecules and ions in the fluidic cavity and channels. Nonlinear stochastic dynamics of Brownian particles is of a particular importance in cellular transport, molecular assembling, information processing, etc. It is shown that nonlinear phenomena cannot be linearized and studied as deterministic. Hence, asymmetric potentials and stochastic forces are examined. The results are demonstrated for a fluidic molecular electronic module. Our objective is to control the transport (motion) of molecules in the fluidic cavity between releasing and binding cites at two membranes. Controlled and uncontrolled particles motion due to distinct forces, gradients and fields is examined using a high-fidelity mathematical model.

2. SYNTHETIC FLUIDIC MOLECULAR ELECTRONIC DEVICES AND MODULES

We propose a 3D topology module which is comprised of interconnected conducting multi-terminal molecules which are encapsulated in the silicon or polymeric enclosure. The silicon inner enclosure is made of porous silicon to form membranes with selective fluidic channels. We prototype pre- and postsynaptic membrane channels, synaptic cleft and cytoplasm. Specific ions, molecules and enzymes can pass through the porous silicon membranes. These passed molecules (activating and regulating information carriers) bind to the specific protein receptor sites, while enzymes free molecules from binding sites. Binding and unbinding of molecules change the electronic properties and folding (conformation) of proteins. Hence, the functionalized proteins change their input-output electronic characteristics and conformation varying the electron transport or ensuring switching. For a cubic module, for example, one may use six distinct membranes at each face with different information carriers (molecules). Correspondingly, the computing and information processing can be performed on the high base (radix) utilizing the selectivity features. This leads to revolutionary advantages compared with the conventional binary logics and memories. Hence, due to selective control (release, propagation, binding and unbinding) of activating and regulating information carriers, we enable multi-valued logics and memory. The aforementioned activating and regulating information carriers are, for example, molecules in the fluidic cavity, neurotransmitters in the synaptic cleft, or biomolecules in the cytoplasm. The ions and molecules that pass through highly-selective fluidic channels and propagate in cavity are controlled by changing the electrostatic potential and thermal gradient. The goal is to achieve a controlled Brownian motion of particles. Distinct control mechanisms allow us to uniquely utilize selective control of different particles ensuring super-high performance and enabling functionality. The proposed solution leads to revolutionary basic and technological advantages at the device and system levels. The fluidic molecular module is coherently supported by the existing and envisioned molecular fabrication technologies that can be used to fabricate a proof-of-concept prototype.

3. MATHEMATICAL MODELING AND CONTROL

Nonlinear stochastic particle dynamics integrates stochastic mechanical, thermal, electromagnetic, noiseinduced and bistable phenomena [2]. For N particles under the asymmetric potentials $V_k(\mathbf{r})$ and forces $F_n(t,\mathbf{r})$, the second-order stochastic differential equations that model Brownian dynamics are usually used [2]. In particular,

$$m_{i}\frac{d^{2}\mathbf{r}_{i}}{dt^{2}} = -F_{v_{i}}\left(\frac{d\mathbf{r}_{i}}{dt}\right) + \sum_{i,j}^{N}F(t,\mathbf{r}_{ij}) + q_{i}\frac{\partial V(\mathbf{r}_{i})}{\partial\mathbf{r}_{i}} + \sum_{i,j}^{N}\frac{\partial V(\mathbf{r}_{ij})}{\partial\mathbf{r}_{ij}} + \xi_{i},$$

$$i = 1, 2, \dots, N-1, N, \qquad (1)$$

where m_i and q_i are the mass and charge; F_v is the viscous friction force, and for one-dimensional propagation $F_v = \eta (dx/dt) = \eta v$; η is the viscous friction coefficient; $\xi(t)$ is the Gaussian white noise, $\langle \xi(t) \rangle = 0$ and $\langle \xi(t) \xi(t') \rangle = 2\eta k_B T \delta(t-t')$; k_B is the Boltzmann constant; T is the absolute temperature.

The equations of motion are derived using the displacement vector \mathbf{r} , velocity vector \mathbf{v} ($\mathbf{v}=d\mathbf{r}/dt$) and extended state vector \mathbf{q} . The electric, magnetic, hydrodynamic, thermal, and other stochastic forces are explicitly defined and integrated using $F_n(t,\mathbf{r})$. One obtains

$$m_{i} \frac{d^{2} \mathbf{r}_{i}}{dt^{2}} = -F_{v_{i}} \left(\frac{d \mathbf{r}_{i}}{dt} \right) + \sum_{i,j,n} F_{n}(t, \mathbf{r}_{ij}) + \sum_{i,k} q_{i} \frac{\partial V_{k}(\mathbf{r}_{i})}{\partial \mathbf{r}_{i}} + \sum_{i,j,k} \frac{\partial V_{k}(\mathbf{r}_{ij})}{\partial \mathbf{r}_{ij}} + f_{r}(t, \mathbf{r}, \mathbf{q}) + \boldsymbol{\xi}_{ri},$$

$$\frac{d \mathbf{q}_{i}}{dt} = f_{q}(t, \mathbf{r}, \mathbf{q}) + \boldsymbol{\xi}_{qi}, \quad i = 1, 2, ..., N-1, N,$$
(2)

where $f_r(t,\mathbf{r},\mathbf{q})$ and $f_q(t,\mathbf{r},\mathbf{q})$ are the nonlinear maps.

The forces $F_n(t,\mathbf{r})$ and potentials $V_k(\mathbf{r})$ of electromagnetic, hydrodynamic, thermal and other origin can be varied by changing distinct physical variables such as voltage, current, temperature gradient, viscosity, concentration, pH, etc. Hence, the varied asymmetric potentials and forces are defined as $V_k(\mathbf{r},\mathbf{u})$ and $F_n(t,\mathbf{r},\mathbf{u})$, where \mathbf{u} is the control vector. Thus, for controlled stochastic systems, the equations of motion to be applied are

$$m_{i} \frac{d^{2} \mathbf{r}_{i}}{dt^{2}} = -F_{v_{i}} \left(\frac{d\mathbf{r}_{i}}{dt} \right) + \sum_{i,j,n} F_{n}(t, \mathbf{r}_{ij}, \mathbf{u}) + \sum_{i,k} q_{i} \frac{\partial V_{k}(\mathbf{r}_{i}, \mathbf{u})}{\partial \mathbf{r}_{i}}$$
$$+ \sum_{i,j,k} \frac{\partial V_{k}(\mathbf{r}_{ij}, \mathbf{u})}{\partial \mathbf{r}_{ij}} + f_{r}(t, \mathbf{r}, \mathbf{q}) + \boldsymbol{\xi}_{ri},$$
$$\frac{d\mathbf{q}_{i}}{dt} = f_{q}(t, \mathbf{r}, \mathbf{q}) + \boldsymbol{\xi}_{qi}, \quad i = 1, 2, ..., N.$$
(3)

The stochastic control problem is formulated as to minimize the performance functional $E \int_{0}^{T} W(\mathbf{r}, \mathbf{q}, \mathbf{u})$ subject to the system dimension (2). In the functional E denotes the

to the system dynamics (3). In the functional, E denotes the expectation symbol, while $W(\mathbf{x},\mathbf{q},\mathbf{u})$ is the performance integrand. The tracking control algorithm is

 $\mathbf{u}=K(\mathbf{e}), \mathbf{e}(t)=\mathbf{r}_{y}(t)-\mathbf{y}(t),$ (4) where $\mathbf{e}(t)$ is the tracking error; $\mathbf{r}_{y}(t)$ is the reference (command) vector; $\mathbf{y}(t)$ is the output vector.

4. NEURON AND MOLECULAR ELECTRONICS

Brain is a complex network of 1×10^{11} neurons with more than 1×10^{14} synaptic interfaces. A neuron, as a complex module, performs information processing, storage, control and other functions. Action potentials, and, perhaps other information-containing signals are transmitted to other neurons by means of very complex and not fully comprehended axo-dendritic, dendro-axonic, axo-axonic and *dendro-dendritic* interactions. For example, biomolecules (neurotransmitters and enzymes) and ions propagate in synaptic cleft, membrane channels and cytoplasm. This transport results in charge distribution, interaction, releasing, binding, unbinding and other mechanisms. There are ongoing discussions concerning system- and device-level considerations as well as fundamental phenomena observed, utilized, embedded and exhibited by neurons. There is no agreement on whether or not a neuron is a device or system, or how the information is transmitted, processed, encoded, stored, controlled, etc.

The directional motion of ions and neurotransmitters is observed in neurons. There is a potential difference across the axonal membrane, and the resting potential is $V_0 = -0.07$ V. The voltage-gated sodium and potassium channels in the membrane result in propagation of action potential with a speed ~ 100 m/sec, and the membrane potential changes from -0.07 V to +0.03 V. The ATP-driven pump restores the Na⁺ and K^+ concentration to their initial values within ~1 msec, making the neuron ready to fire again, if triggered. Neurons can fire more than 1×10^3 times per second. Consider a membrane with the uniform thickness h. For the voltage differential $\Delta V = (V_A - V_0)$ across the membrane, the surface charge density $\pm \rho_s$ inside/outside membrane is $\rho_s = \varepsilon E$, where the electric field strength is $E=\Delta V/h$. Here, ε is the membrane permittivity. The total active surface area is $A = \pi dL_A$, where d is the diameter; L_A is the active length. The total number of ions that propagate during firing is $n_I = \frac{A\rho_S}{q_I} = \frac{\pi dL_A \varepsilon_0 \varepsilon_r (V_A - V_0)}{q_I h}$, where ε_r is the relative

permittivity; q_I is the ionic charge. Let $d=1\times10^{-5}$ m, $L_A=1\times10^{-4}$ m, $\varepsilon_r=2$, $V_A=0.03$ V, $V_0=-0.07$ V and $h=8\times10^{-9}$ m. For Na⁺ ions, $q_{\text{Na}}=e$, where e is the electron charge. One finds that there is $n_{\text{Na}}=4.34\times10^5$ ions.

Other hypotheses have been emerged regarding the functionality of neurons, as well as the role of biomolecules and ions as information processing and carrying particles.

5. CONTROLLED FLUIDIC MOLECULAR MODULE

Neurons that perform information processing, memory storage, communication and other functions are not solidstate electronic devices fabricated using semiconducting materials and metallic interconnect. Instead of using the electron transport in the solid-state devices (FETs, BJTs and other transistors), the controlled electron transport or folding transformations (switching) in proteins are uniquely utilized in our 3D topology fluidic modules. The overall scheme is: molecule release – transport – binding/ unbinding – changes (electronic or mechanical). In neurons, neurotransmitters propagate through the synaptic cleft, while potassium, sodium, chloride, calcium and other ions pass through selective ionic channels of cell membranes. The ionic channels are opened and closed due to binding of released neurotransmitters.

Consider a spherical particle with radius *r* that moves at velocity *v* in the liquid with viscosity μ . For the laminar flow, the Stokes's law gives the viscous friction (drag) force as $F_v = \eta v$; where η is the viscous friction (drag) coefficient which is found as $\eta = 6\pi\mu r$. The inverse of the drag coefficient is called the mobility, $\mu_B = 1/\eta = 1/6\pi\mu r$. The diffusion constant of a particle *D* is related to the mobility and the absolute temperature by the Einstein fluctuation dissipation theorem, e.g., $D = k_B T \mu_B$.

Using the ionic radii of Na⁺ and K⁺ ions $r_{Na}=0.95\times10^{-10}$ m and $r_{K}=1.33\times10^{-10}$ m, for $\mu=9.5\times10^{-4}$ N-s/m² at 37°C (*T*=310.15 K), one finds $D_{Na}=2.52\times10^{-9}$ m²/s and $D_{K}=1.8\times10^{-9}$ m²/s, close to the experimental values $D_{Na}=1.33\times10^{-9}$ m²/s and $D_{K}=1.96\times10^{-9}$ m²/s. By regulating the ionic channels, the cell controls the ionic flow across the membrane. The membrane conductance *g* has been experimentally measured using an expression I=gV. It is found that for the sodium and potassium open channels, the conductance is in the range of $g=2\times10^{-11}$ [A/V]. The current that flows through the channel is estimated as $I=q_{I}J_{I}A$, where q_{I} is the charge on one ion; J_{I} is the ionic flux, $J_{I}=cv$; *c* is the ionic concentration; *v* is the ion velocity; *A* is the channel cross-sectional area. The average velocity of ion in the electrostatic field is estimated using the mobility and force

as
$$v = \mu_B F = \mu_B q_I E = \mu_B q_I V/x$$
. Hence, one has $v = \frac{D}{k_B T} q_I \frac{V}{x}$.

Our goal is to control the Brownian particles (molecules) in the fluidic cavity. Distinct 3D topology devices and modules can be devised. Using molecules that are released, controlled and attached to the binding cites, the synthetic fluidic molecular electronic module is schematically illustrated in Figure 1. It has membranes with selective fluidic channels (molecular releasing cite) and multi-terminal processing circuits with binding cites. The released molecules propagate in the fluidic cavity. The release and propagation mechanism is regulated by a control apparatus. This apparatus is comprised of polypeptide or molecular circuits which vary the temperature gradient and an electric field. The electron transport in the anchored processing polypeptide or molecular circuits changes as molecules bind and unbind.



Figure 1. Fluidic molecular electronic module and interaction diagram

The number of molecules in the cavity depends on the concentration and is regulated by the selective molecule release. Consider the propagation of molecules through the $10 \times 10 \times 10$ nm cavity. Let the concentration of two positively charged molecules (\mathbf{A}^+ and \mathbf{B}^+) be 10 mM which is close to neurotransmitter concentration. Our goal is to control a single molecule \mathbf{C}^- . For the considered devise with the separation between releasing and binding cites on opposite membranes 10 nm (L=10 nm.), we study six \mathbf{A}^+ , six \mathbf{B}^+ and a single \mathbf{C}^- molecule. One can perform computing, processing and information storage because molecules interact with each other as well as bind to molecular receptors (polypeptides) on the membrane binding cites.

We examine the motion of 13 particles in threedimensional space. This results in 117 first-order stochastic differential equations (3), i=1,...,13. The uncontrolled motion results due to temperature gradient and hydrodynamic stochastic fields. Those effects are integrated using asymmetric potentials $V_1(\mathbf{r})$ and $V_2(\mathbf{r})$ in term $\sum_k q_i \frac{\partial V_k(\mathbf{r}_i, u)}{\partial \mathbf{r}_i}$. The media viscosity, pH and concentration

are not considered to be control variables because it is not feasible to effectively vary them. As a control variable, we consider the varying electric field E_z . Therefore, by changing u, we vary $V_3(\mathbf{r}, u)$ and $F_3(\mathbf{r}, u)$.

The masses, diffusion coefficients (at 37^oC) and ionic radii of \mathbf{A}^+ , \mathbf{B}^+ and \mathbf{C}^- molecules are: $m_{\rm A}=3\times10^{-25}$ kg, $m_{\rm B}=4\times10^{-25}$ kg, $m_{\rm C}=5\times10^{-25}$ kg, $r_{\rm A}=2\times10^{-10}$ m, $r_{\rm B}=2.2\times10^{-10}$ m, $r_{\rm C}=2.4\times10^{-10}$ m, $D_{\rm A}=1\times10^{-9}$ m²/s, $D_{\rm B}=1.5\times10^{-9}$ m²/s and $D_{\rm C}=2\times10^{-9}$ m²/s. The relative permittivities of presynaptic and postsynaptic membranes are $\varepsilon_{rp}=2.3$ and $\varepsilon_{rp}=2.1$.

For a molecular fluidic module we first examine the non-controlled equations (2). The solution defines the position and velocity of each Brownian particle at time *t*. Let the C⁻ molecule is released at the origin, and this molecule should reach the receptor site. The initial positions of A⁺ and B⁺ molecules were assigned randomly. The electric field intensity is related to the potential as $\mathbf{E} = -\nabla V$. The particle and particle-membrane interactions are studied. The potential is derived using the superposition of the point, line, surface and volume charges as

$$V_{i} = V_{ai} + V_{ei} + \sum_{j=1}^{2} V_{mij} + \sum_{i,j=1,i\neq j}^{N} V_{Eij} + \sum_{i,j=1,i\neq j}^{N} V_{Cij}, \qquad (5)$$

where V_{ai} is the asymmetric periodic potential with $l \neq \text{const}$ (V_{ai} results due to the temperature gradient and hydrodynamic field); V_{ei} is the external potential including the applied membrane potentials; V_{mij} is the interacting Brownian particle-membrane potential; V_{Eij} is the electrostatic potential due to the charge; V_{Cij} is the Coulomb potential due to *j*th Brownian particle.

The Lorenz force on a Brownian particle possessing the charge *q* is $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$, while using the surface charge density ρ_{v} , one obtains $\mathbf{F} = \rho_{v}(\mathbf{E} + \mathbf{v} \times \mathbf{B})$. The magnetic field force is negligible, and the electrostatic force is studied.

The asymmetric control potential $V(\mathbf{r}, u)$ is given as

$$W(\mathbf{r},u) = \left(\frac{\sin\sqrt{1 \times 10^{19} x^2 + 1 \times 10^{19} y^2 + d}}{\sqrt{1 \times 10^{19} x^2 + 1 \times 10^{19} y^2 + d}} + \frac{1}{4}\right) e^{-1 \times 10^8 z} \left[\cos^2\left(\frac{2n\pi}{L}z\right) + u \tan^{-1}e^{\frac{z}{L}}\right]$$

where d=0.00001 and n=5. The three-dimensional plots for $V(\mathbf{r},u)$, as x and y vary from -5 to 5 nm for u=1 and three z values (0, 3, 6 and 9 nm), are documented in Figure 2.



Figure 2. Potential $V(\mathbf{r}, u)$, u=1 in the fluidic cavity

The analysis of the directed uncontrolled (u=0)Brownian motion is performed using the asymmetric threedimensional interaction potentials $V(\mathbf{r})$. The external force $F(t,\mathbf{r}_{ij})=0$, and the electric, hydrodynamic and thermal forces are considered. Figure 3 documents the dynamics for the $\mathbf{C}^$ molecule displacement z(t). The velocity $v_z(t)$ and force $F_z(t)$ are documented in the arbitrary units. The molecule motion is achieved under the uncontrolled stochastic thermal and hydrodynamic fields. Three-dimensional evolutions for two different simulation runs are shown in Figure 3.

The control law is designed as

$$u = \operatorname{sat}(-1.5 \times 10^{-5} e - 0.93 \times 10^{-5} \int e dt), \ e(t) = r_z(t) - z(t).$$
(6)

The transient dynamics and the evolution for the C^- molecule in the closed-loop system (3)-(6) for the variable of the most interest (*z*, *v_z* and *F_z*) are reported in Figure 4. The molecule reaches the reference $r_z=10$ nm. The settling time

is $0.034 \ \mu$ sec. The comparison of the transient dynamics, as documented in Figures 3 and 4, provides the important information for the controlled and uncontrolled motions.



Figure 3. Uncontrolled molecule evolution in three dimensions



Figure 4. Controlled molecule evolution in three dimensions

6. CONCLUSIONS

We solved several key problems in devising, designing and developments of high-performance fluidic molecular electronic modules with enabling functionality. It was documented that molecular computing, processing and memory can be accomplished utilizing novel physical phenomena. The controlled motion of molecules was examined.

REFERENCES

- S. E. Lyshevski, Three-Dimensional Molecular Electronics, Integrated Circuits and Information Processing Platforms, in Handbook of Nanoscience, Engineering and Technology, and in Handbook of Molecular and NanoElectronics Ed. S. E. Lyshevski, CRC Press, Boca Raton, FL, 2006.
- M. A. Lyshevski, "Brownian ionic and neurotransmitter dynamics and its application in nanobioelectronics," *Proc. IEEE Conference on Nanotechnology*, Nagoya, Japan, pp. 498-500, 2005.