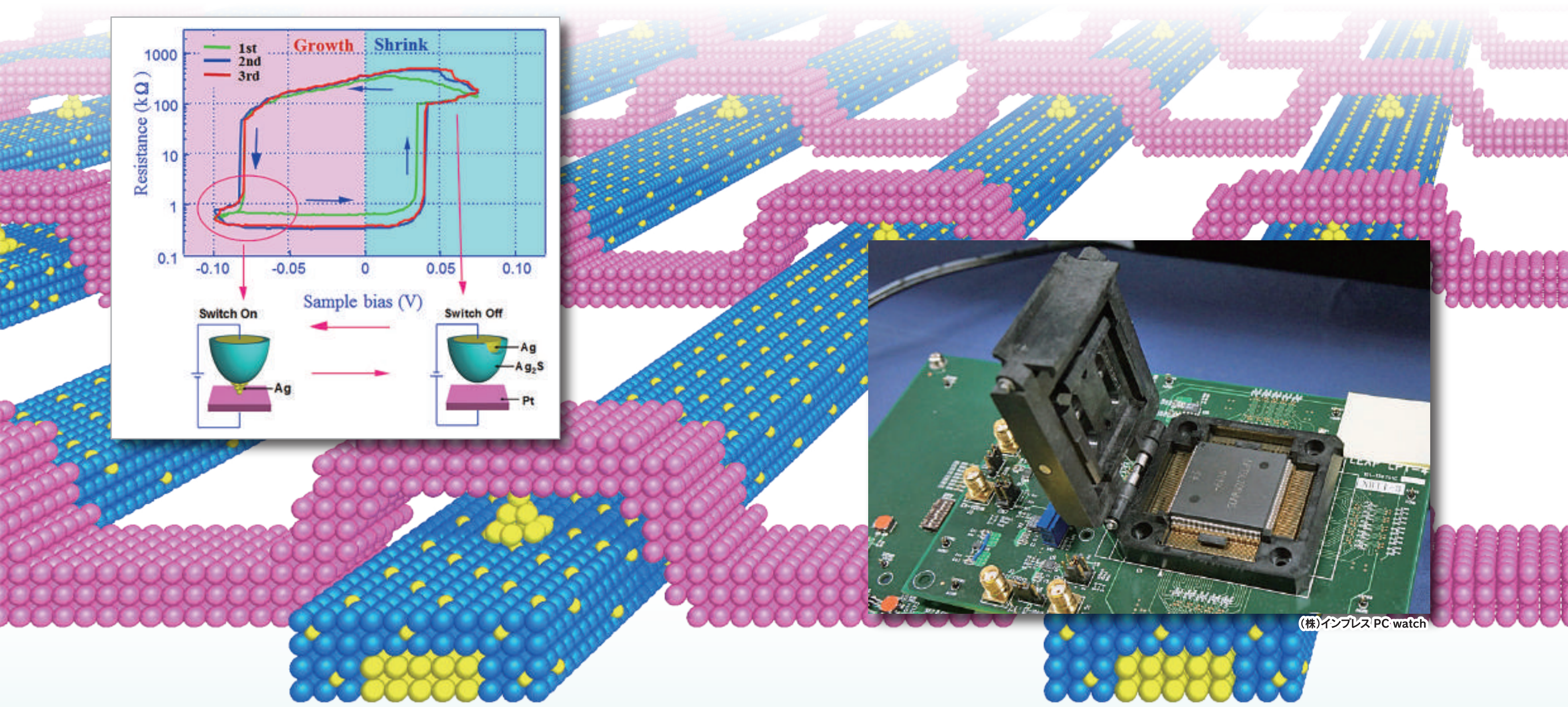
日本発の独創的な IT デバイス「原子スイッチ」の実用化を祝う国際シンポジウム
－ NIMS で開発された原子スイッチが NEC によって実用化 －

International Symposium on

Atomic Switch: Invention, Practical Use and Future Prospects

ABSTRACTS of Presentations
&
PUBLICATION LIST related to the atomic switch



(株)インプレス PC watch

March 28, 2017

Meeting Room “SUBARU”
Okura Frontier Hotel Tsukuba

MANA wpi NIMS NEC JST

Welcome address

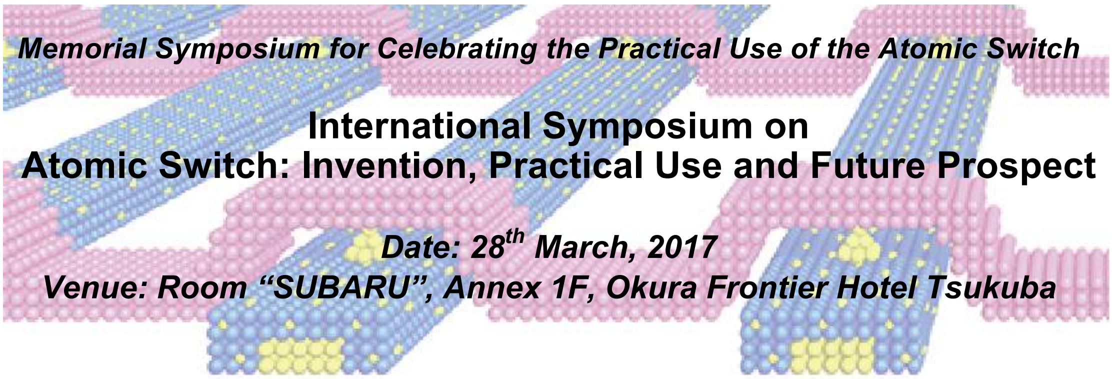
The “atomic switch”, which was invented in 2001 and has been investigated at MANA/NIMS for about 10 years with the support of JST and MEXT and in collaboration with NEC, has come into practical use as the “NEC AtomSW-FPGA”, which will soon be used in robots and space satellites for example. This is because the atomic switch is not only compact and has low power-consumption, but also because it is scarcely influenced by electromagnetic noise and radiation (including cosmic rays).

To celebrate the practical use of the atomic switch, which is a novel nanoelectronics device originating in Japan, we hold a memorial symposium as follows. At the symposium, we will also present information about how the atomic switch has begun to be used for brain-type information processing and for completely novel functional nanodevices. We believe that this symposium will be useful for all the scientists and engineers who are interested in nanoscale devices in relation to AI and IoT. Please participate in this symposium.

私どもが2001年に発明し、JSTや文部科学省の支援を受け、NECと共同して、MANA/NIMSにおいて研究を続けてきた「原子スイッチ」が、このたび“NEC AtomSW-FPGA”として実用化され、ロボットや人工衛星などでの利用が目指されています。原子スイッチは、コンパクトで低消費電力であるだけでなく、電磁ノイズや放射線（宇宙線）による誤動作がほとんどないためです。

この機会に、日本発の独創的ナノエレクトロニクス・デバイスである「原子スイッチ」の実用化を祝うと共に、「原子スイッチ」が脳型の情報処理や全く新しい高機能デバイスへと展開し始めている状況を展望するシンポジウムを開催することにしました。AIやIoTに関心のある方には必ずお役に立つと信じます。ぜひご参加ください。

Masakazu Aono
Director,
WPI Center for Materials Nanoarchitectonics (MANA),
National Institute for Materials Science (NIMS)



Memorial Symposium for Celebrating the Practical Use of the Atomic Switch

International Symposium on Atomic Switch: Invention, Practical Use and Future Prospect

Date: 28th March, 2017
Venue: Room "SUBARU", Annex 1F, Okura Frontier Hotel Tsukuba

PROGRAM

March 27th

18:00 - 20:00 *Reception （Bar Continental, 11 F, Okura Frontier Hotel Tsukuba）*

March 28th

09:00 - 09:30 *Registration*

Opening

（Chair: Tomonobu Nakayama）

09:30 - 09:40 *Opening address （Scope of Symposium）*
Masakazu Aono (Director, MANA/NIMS)

09:40 - 09:50 *Greeting*
Kazuhito Hashimoto (President of NIMS)

09:50 - 10:00 *Greeting*
Motoo Nishihara (Senior Vice President, NEC Corp.)

10:00 - 10:10 *Greeting*
Jun'ichi Sone (Senior Fellow, JST)

< Part I > From Invention to Practical Use of the Atomic Switch

（Chair: James K. Gimzewski）

10:10 - 10:50 *Invention and Development of the Atomic Switch*
K. Terabe[1], T. Hasegawa[2], T. Nakayama[1], M. Aono[1] ([1]MANA/NIMS, [2]Waseda Univ.)

10:50 - 11:30 *Pathway to Atomic Switch based Programmable Logic*
T. Sakamoto[1], M. Tada[1], M. Miyamura[1], Y. Tsuji[1], R. Nebashi[1], A. Morioka[1], N. Banno[1], K. Okamoto[1], N. Iguchi[1], H. Hada[1], T. Sugibayashi[1], K. Terabe[2], T. Hasegawa[2], M. Aono[2] ([1]NEC Corp., [2]MANA/NIMS)

11:30 - 11:55 *Atom-Switch FPGA Application for IoT Sensing System in Space*
H. Hihara (NEC Space Technologies, Ltd.)

11:55 - 12:10 *Group Photo*

12:10 - 13:20 *Lunch*

13:20 - 13:50 ***Poster Session with coffee***

< Part II > New Developments of the Atomic Switch

(Chair: Kazuya Terabe)

13:50 - 14:30 【Special Lecture】
Nanoscale Electrochemical Studies: How can We Use the Atomic Switch
I. Valov[1,2], T. Hasegawa[3], S. Tappertzhofen[2], T. Tsuruoka[4], M. Lübben[2], R. Waser[1,2], M. Aono[4] ([1]Research Centre Jülich, [2]RWTH-Aachen Univ., [3]Waseda Univ., [4]MANA/NIMS)

14:30 - 14:55 *Development of Three-terminal Atomic Switches and Related Topics*
T. Hasegawa[1], T. Tsuruoka[2], C. Lutz[1,2], Q. Wang[3], Y. Itoh[2], H. Tanaka[4], T. Ogawa[5], S. Watanabe[6], S. Yamaguchi[6], M. Aono[2] ([1]Waseda Univ., [2]MANA/NIMS, [3]Lanzhou Uviv., [4]Kyushu. Inst. Tech., [5]Osaka Univ., [6]Univ. Tokyo)

14:55 - 15:20 *Artificial Synapses Realized by Atomic Switch Technology*
T. Tsuruoka[1], T. Ohno[1,2], A. Nayak[1,3], R. Yang[1,4], K. Terabe[1], T. Hasegawa[1,5], J. K. Gimzewski[1,6], M. Aono[1] ([1]MANA/NIMS, [2]Tohoku Univ., [3]IIT-Patna, [4]Huazhong Univ. Sci. Tech., [5]Waseda Univ., [6]UCLA)

15:20 - 15:35 *Coffee Break*

(Chair: Ilia Valov, Zdenka Kuncic)

15:35 - 16:00 *Atom Switches for Neuroarchitectonics*
J. K. Gimzewski[1,2], A. Z. Stieg[2], R. Aguilera[2], K. Scharnhorst[2], E. C. Demis[2], H. O. Sillin[2], E. J. Sandouk[2], A. V. Avizienis[2], M. Aono[1] ([1]MANA/NIMS, [2]UCLA,)

16:00 - 16:25 *Emerging Functionality of Neuromorphically Networked Structures*
T. Nakayama[1], R. Higuchi[1], Z. Kuncic[2], Y. Shingaya[1], J. K. Gimzewski[1,3], M. Aono[1] ([1]MANA/NIMS, [2]Univ. Sydney, [3]UCLA)

16:25 - 16:50 *Atomistic Simulations for Understanding Microscopic Mechanism of Atomic Switches*
S. Watanabe, B. Xiao, W. Li (Univ. Tokyo)

16:50 - 17:15 *Atomic Switch Based Decision Making*
S. -J. Kim[1], T. Tsuruoka[1], T. Hasegawa[2], M. Aono[3], K. Terabe[1], M. Aono[1] ([1]MANA/NIMS, [2]Waseda Univ., [3]Tokyo Inst. Tech.)

17:15 - 17:40 *Nanoionic Devices for Physical Property Tuning and Enhancement*
T. Tsuchiya, T. Tsuruoka, K. Terabe, M. Aono (MANA/NIMS)

17:40 - 17:45 *Closing Remarks*
Kazuya Terabe (MANA/NIMS)

18:00 - 20:00 *Banquet*
(Banquet Hall "SUBARU", Annex 1F, Okura Frontier Hotel Tsukuba)

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Steering Committee

- Gimzewski, James K. [Chair]
- Kishi, Teruo
- Kuroki, Toshio
- Sone, Jun'ichi
- Waser, Rainer
- Welland, Mark
- Williams, Stan
- Yamaguchi, Shu

Organizing Committee

- Aono, Masakazu [Chair]
- Gimzewski, James K.
- Hasegawa, Tsuyoshi
- Nakayama, Tomonobu
- Sakamoto, Toshitsugu
- Sugibayashi, Tadahiko
- Terabe, Kazuya
- Tsuruoka, Tohru
- Tsuchiya, Takashi
- Valov, Ilia
- Waser, Rainer

Local Organizing Committee

- Aono, Masakazu
- Nakayama, Tomonobu [Co-chair]
- Terabe, Kazuya [Co-chair]
- Tsuruoka, Tohru
- Tsuchiya, Takashi
- Kobayashi, Michiko

Poster Session

P01 *Development of Video Encoding using Atomic-Switch Based FPGA*

T. Sakamoto[1], M. Tada[1], M. Miyamura[1], X. Bai[1], Y. Tsuji[1], R. Nebashi[1], A. Morioka[1], N. Banno[1], K. Okamoto[1], N. Iguchi[1], H. Hada[1], T. Sugibayashi[1] ([1]NEC Corp.)

P02 *An Evaluation of Single Event Effect by Heavy Ion Irradiation on Atom Switch ROM/FPGA*

K. Takeuchi[1], M. Tada[2], T. Sakamoto[2], H. Shindo[1], S. Kuboyama[1], A. Takeyama[3], K. Suzuki[1] ([1]JAXA, [2]NEC Corp., [3]QST)

P03 *Solid-Polymer-Electrolyte-Based Atomic Switches*

T. Tsuruoka[1], K. Krishnan[1,2], S. R. Mohapatra[1,3], S. Wu[1,4], M. Aono[1] ([1]MANA/NIMS, [2]CSIR-CERI, [3]NIT-Silchar, [4]QHTZ)

P04 *Psychological Memorization Model Demonstrated by Atomic Switches*

T. Ohno[1,2], T. Hasegawa[2,3], T. Tsuruoka[3], K. Terabe[3], A. Nayak[2,4], J. K. Gimzewski[2,5], M. Aono[3] ([1]Tohoku University, [2]MANA/NIMS, [3]Waseda Univ., [4]IIT-Patra, [5]CNSI/UCLA)

P05 *Neuromorphic Atomic Switch Networks for Natural Computing*

K. Scharmhorst[1], R. Aguilera[1], **A. Stieg**[1], J. K. Gimzewski[1,2] ([1]UCLA, [2]MANA/NIMS)

P06 *Investigation of Dynamic Phenomena in Polymer-coated Ag Nanowire Network*

R. Higuchi[1], Y. Shingaya[1], M. Li[1], Z. Kuncic[2], J. K. Gimzewski[1,3], M. Aono[1], T. Nakayama[1,4] ([1]MANA/NIMS, [2]Univ. Sydney, [3]CNSI/UCLA, [4]Univ. Tsukuba)

P07 *Conduction through Thermosenstive Networks*

R. G. Shrestra[1], R. Higuchi[1], Y. Shingaya[1], S. Samitsu[2], T. Nakayama[1] ([1]MANA/NIMS, [2]PMU/NIMS)

P08 *Functionalized PANI Network Conductor towards Future Computation*

L. Qiao[1,2], R. Higuchi[2], Y. Shingaya[2], Y. Kato[2], K. Tanaka[2], T. Nakayama[1,2] ([1]Univ. Tsukuba, [2]MANA/NIMS)

P09 *MP-AFM Measurement of Metal and Polymer Nanowires as Basic Components of Neuromorphic Network System*

Y. Shingaya[1], R. Higuchi[1], M. Li[1], S. Endo[2], O. Kubo[2], M. Aono[1], T. Nakayama[1,3] ([1]MANA/NIMS, [2]Osaka Univ., [3]Univ. Tsukuba)

P10 *'Tug of War' Devices for Interconnection of Artificial Synapses*

C. Lutz[1,2], T. Hasegawa[1], T. Chikyo[2] ([1]Waseda Univ., [2]MANA/NIMS)

P11 *Study of Atom Diffusion in Amorphous Structure with Neural Network Potentials*

W. Li[1], Y. Ando[2], E. Minamitani[1], S. Watanabe[1,3] ([1]Univ. Tokyo, [2]CD-FMat/AIST,

[3]CMI2/NIMS)

P12 *Effects of the Composition of* Ta_2O_5 *Films on the Resistive Switching Properties of* Ta_2O_5*-Based Atomic Switches*

C. Mannequin[1,2], T. Tsuruoka[2], T. Hasegawa[2,3], M. Aono[2] ([1]Univ. Tsukuba, [2]MANA/NIMS, [3]Waseda Univ.)

P13 *Electrical-Pulse-Induced Resistivity Modulation in* $Pt/TiO_{2-\delta}/Pt$ *Multilayer Device Relevant to Nanoionic-Based Neuromorphic Function*

K. Kawamura[1], T. Tsuchiya[2], K. Terabe[2], T. Higuchi[1] ([1]Tokyo Univ. Sci., [2]MANA/NIMS)

P14 *Surface Proton Conduction on Yttria-stabilized Zirconia Thin Film for Nanoionic Devices Application*

M. Takayanagi[1], T. Tsuchiya[2], M. Minohara[3], M. Kobayashi[3], K. Horiba[3], H. Kumigashira[3], T. Higuchi[1] ([1]Tokyo Univ. Sci. [2]MANA/NIMS, [3]KEK)

P15 *Electrical Property of* $Nd_{0.6}Sr_{0.4}FeO_3$ *Thin Film Deposited by RF Magnetron Sputtering Method*

W. Namiki[1], T. Tsuchiya[2], M. Minohara[3], M. Kobayashi[3], K. Horiba[3], H. Kumigashira[3], T. Higuchi[1] ([1]Tokyo Univ. Sci., [2]MANA/NIMS)

International Symposium on
Atomic Switch
2017

Opening

Opening address

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Greeting

Name (Title):	Kazuhito Hashimoto (President, NIMS)	
Affiliation:	National Institute for Materials Science (NIMS)	
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Greeting

Name (Title):	Motoo Nishihara (Senior Vice President, NEC Corp.)	
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Greeting

Name (Title):	Jun’ichi Sone (Senior Fellow, JST)	
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International Symposium on
Atomic Switch
2017

Oral Presentation

Presentation Title:

Invention and Development of the Atomic Switch

Authors:
°Kazuya Terabe[1], Tsuyoshi Hasegawa[1,2], Tomonobu Nayakama[1], and Masakazu Aono[1]

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1. International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan
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Abstract:

A great number of electronics devices are used in the information and communications equipment, and upgrading of that equipment largely depends on improving the performance of semiconductor devices, which are operated by the movement of electrons within semiconductors. Though semiconductor devices have seen remarkable progress with technological development in miniaturization and integration, it is currently feared that the progress is beginning to slow. Thus, it is also becoming essential to create devices that operate on a completely new set of principles.

Our invention of an atomic switch with a novel operating principle, using the movement of atom (ion), was serendipitous in a sense. In earlier studies, we were working on an experiment where atoms were arranged into lines in order to draw on a substrate by generating a high electric field at a tip of a scanning tunneling microscope's (STM) probe made of an electron and ion mixed conductor materials, and dripping metal atoms one at a time from the tip. In doing so, without forethought, we found that by controlling the voltage applied to the STM tip, A protrusion at that tip, consisting of a small amount of metallic atoms, could be grown and shrunk. Fig. 1 shows the growth and shrinkage of Ag atom protrusion at the STM tip of electron and Ag ion mixed conductor Ag_2S. The Ag protrusion at the tip grew and shrank reversibly when the polarity of V_s and magnitude of I_t were changed, in which V_s and I_t are a sample bias and tunneling current, respectively. The conditions of V_s and I_t were changed in the order of 1, 2, 1, 3, 4, and 3, and this sequence was repeated three times in Fig.1.[1]

We immediately came up with the idea of using these reversible processes for atomic-scale electrical switching. In order to examine the atomic switch idea, we cut off the feedback function of the STM so as to keep the height of the STM tip relative to the substrate constant, and observed a switching hysteresis. Based on this discovery of the interesting solid electrochemical phenomena on the atomic scale, thereafter, we have found various unique properties and valuable functions in developed atomic switches.[2-4]

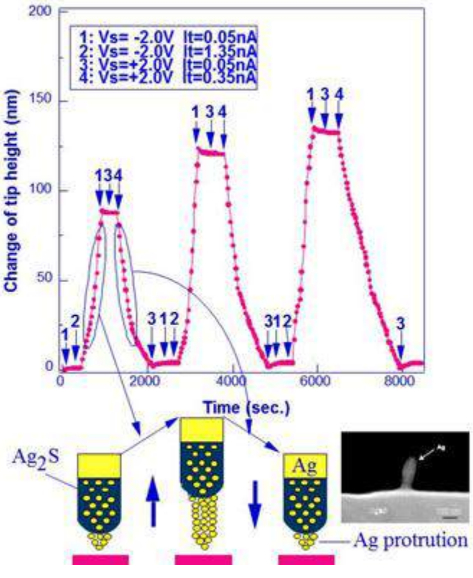

Fig. 1 Reversible growth and shrinkage of the Ag protrusion at an electron and Ag-ion mixed conductor STM tip.

[1] K. Terabe, T. Nakayama, H. Hasegawa, M. Aono, J. Appl. Phys. **91**, 10110 (2002), [2] K. Terabe, T. Hasegawa, T. Nakayama, M. Aono, Riken Rev. **37**, 7 (2001), [3] K. Terabe, T. Hasegawa, T. Nakayama, M. Aono, Nature, **433**, 47 (2005), [4] K. Terabe, M. Aono, Oyo Butsuri, **85** 364 (2016) *in Japanese.*

Presentation Title:

Pathway to Atomic Switch Based Programmable Logic

Authors:
°T. Sakamoto[1], M. Tada[1], M. Miyamura[1], X. Bai[1], Y. Tsuji[1], R. Nebashi[1], A. Morioka[1], N. Banno[1], K. Okamoto[1], N. Iguchi[1], H. Hada[1], T. Sugibayashi[1], K. Terabe[2], T. Hasegawa[2], and M. Aono[2]

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Abstract:

We have been developing atomic-switch [1] based FPGA [2]. Atom switch with a large ON/OFF conductance ratio, non-volatility, and small feature size is suitable for configuration switch in FPGA. The novel switch is composed of the solid electrolyte sandwiched between Cu and Ru. The conduction bridge is formed in the solid electrolyte by applied a positive voltage to the Cu electrode, resulting in the low resistive state (Fig. 1(a)).

ASIC has the highest performance and lowest power consumption but it has very low flexibility. Compared with ASIC, FPGA has better flexibility. Compared with CPU, FPGA has better energy efficiency. Atomic-switch based FPGA achieves both high-energy efficiency and high performance (Fig. 1(b)).

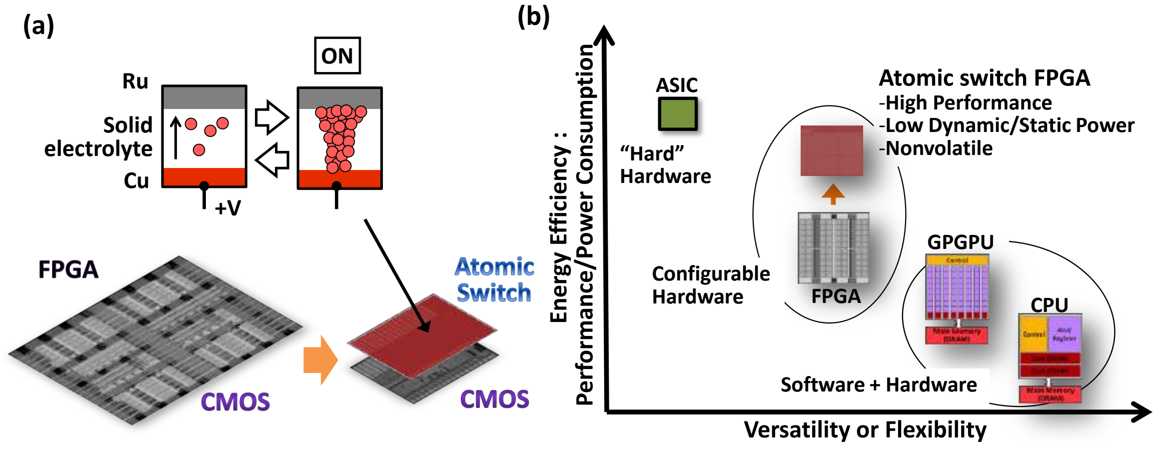

Fig. 1 (a) SRAM and pass transistor in conventional FPGA is replaced by resistive switch (Atomic switch), resulting in reducing circuit area and power consumption. (b) Various Si chips in terms of energy efficiency and versatility.

References:

[1] K. Terabe, et al., "Quantized conductance atomic switch", Nature **433**, 47 (2005).
[2] M. Miyamura, et al., "0.5-V Highly Power-Efficient Programmable Logic using Nonvolatile Configuration Switch in BEOL", Proceedings of the 2015 ACM/SIGDA International Symposium on Field-Programmable Gate Arrays, pp. 236-239 (2015).

Presentation Title:

Atom-Switch FPGA Application for IoT Sensing System in Space

Authors:
°Hiroki Hihara[1]

Affiliation:
1. NEC Space Technologies, Ltd.

Email: h-hihara@bc.jp.nec.com

Abstract:

The Internet of Things (IoT) has been envisioned as a fundamental infrastructure that will bring about useful information and knowledge resulting in efficiency and growth in industry and improved comfort and safety in human life. Sensors, networks, and information technology (IT) are designated as key technology elements to make IoT a practical knowledge framework. IoT is to be used for supporting so-called lifeline as energy supply, water works, traffic control, logistics, broadcasting, and telecommunication. Everything is to be connected through Machine to Machine (M2M) network anytime and anywhere to realize the IoT framework.

Space systems, such as satellites, can be identified as sensor nodes and relay nodes among IoT applications. It is integrated with ground systems, and wide range of collected information must be transmitted through the limited transmission capacity of existing network. Therefore, the extraction of useful data through signal processing using embedded processors on satellites is essential as shown in Fig. 1. Re-writable Field Programmable Gate Arrays (FPGAs) without configuration memories, as atom-switch FPGAs, are required for the purpose, because the most

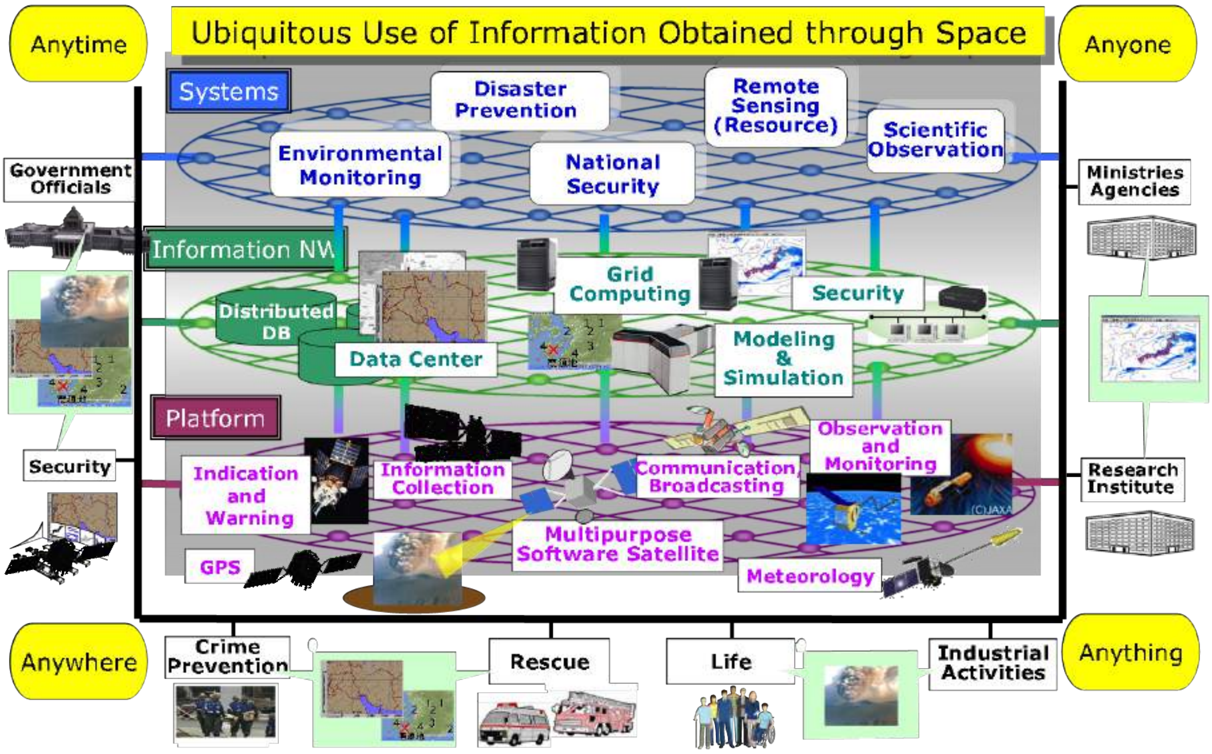

Fig. 1 IoT using embedded signal processors.[1]

demanded characteristics on satellites is a continuous operation in harsh environment with background radiation on orbit, and thus soft-error free FPGAs as atom-switch FPGAs are most promising devices for satellite applications.

Low power consumption is another demanding characteristics for realizing less heat dissipation indispensable to space applications operating in exoatmosphere, because heat dissipation path is limited within chassis conduction. We found that atom-switch FPGAs also have idealistic characteristics for this issue.

[1] http://www.nec.com/en/global/solutions/space/remote_sensing/

Presentation Title:

Nanoscale Electrochemical Studies: How can We Use the Atomic Switch

Authors:
°Ilia Valov[1], Tsuyoshi Hasegawa[2], Stefan Tappertzhofen[1], Tohru Tsuruoka[2], Michael Lübben[1], Rainer Waser[1], and Masakazu Aono[2]

Affiliation:
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2. International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan

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Abstract:

Understanding and controlling the processes of transfer of mass and charge at the nano- and sub-nanoscale is of primary importance for modern science and technology in fields such as nanoelectronics, nanoionics, energy conversion and storage, information technology etc. However, approaching atomic dimensions, material instabilities and instrumentation limits restrict the resolution and hinder more detailed insight. A significant step ahead in that respect has been initiated by studies on resistive switching memories and the invention of the atomic switch.

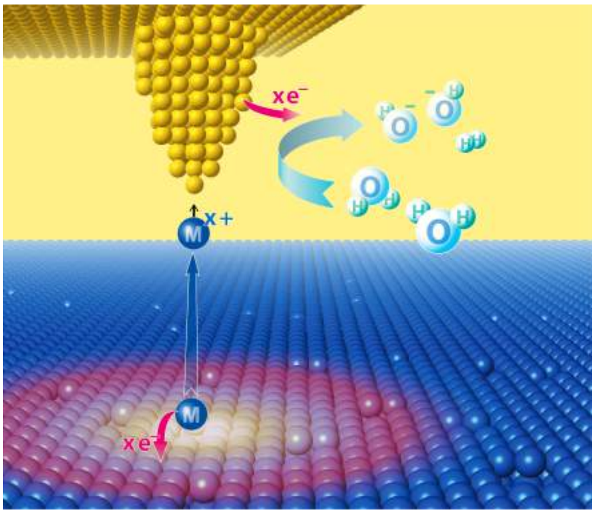

Fig. 1 Atomic switch used for ultra-high resolved electrochemical studies

In this contribution the use of the atomic switch for nanoscale, and even atomically resolved electrochemical studies will be demonstrated. It will be shown that properties of matter changes and the border between definitions for insulators, semiconductors and electrolytes blurs at low dimensions and even high-k materials such as SiO_2, Ta_2O_5, HfO_2 etc. can conduct ions at the nanoscale.

Case samples of potentiostatic and potentiodynamic electrochemical measurements using atomic switch will be highlighted. The role of the electrode materials and their electrocatalytic activity will be discussed. It will be shown that STM in atomic switch approach allows to neglect the electronic conductivity of the samples and enables the highest mass and charge resolution measurements.

Presentation Title:

Development of Three-terminal Atomic Switches and Related Topics

Authors:
°Tsuyoshi Hasegawa[1,2], Tohru Tsuruoka[2], Carolin Lutz[1], Qi Wang[2], Yaomi Itoh[2], Hirofumi Tanaka[3], Takuji Ogawa[4], Satoshi Watanabe[5], Shu Yamaguchi[5], and Masakazu Aono[2]

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4. Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, 560-0043, Japan
5. Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

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Abstract:

Atomic switch has supra advantages over other nonvolatile switches, such as its higher on/off ratio, very low resistance in its on state, and the scalability to the atomic scale. The novel characteristics brought us to use the device as a programmable switch in FPGAs, as introduced by Sakamoto et al. in this symposium.

When we compare the two-terminal structure and the three-terminal structure, the three-terminal structure has an advantage over two-terminal structures in logic applications. Since that the electrical connection and disconnection in the three-terminal structure is controlled by a gate that is electrically separated by a signal line, i.e., a source and a drain, power consumption can be much decreased than that of the two-terminal atomic switches. Although the cell (switch) size becomes larger than that of two-terminal atomic switches, this advantage brought us to develop several three-terminal atomic switches. Figure 1 shows one type of the three-terminal atomic switches, which we call 'Atom Transistor'.[1,2] As expected, it operates with very much small power consumption both in the standby mode and the operating mode. In the operation, it is required to limit the amount of metal cations diffusing to the channel region. Although it was the most difficult challenge in the development, we solved the issue. Moreover, we developed another type of three-terminal atomic switch based on the understanding.[3,4] In the presentation, we will introduce the history and the present status of these three-terminal atomic switches.

[1] T. Hasegawa et al., APEX **4**, 15204 (2011).
[2] Q. Wang et al., Adv. Mater. **27**, 6029 (2015).
[3] Q. Wang et al., Appl. Phys. Lett. **102**, 233508 (2013).
[4] C. Lutz et al., Nanoscale **8**, 14031 (2016).

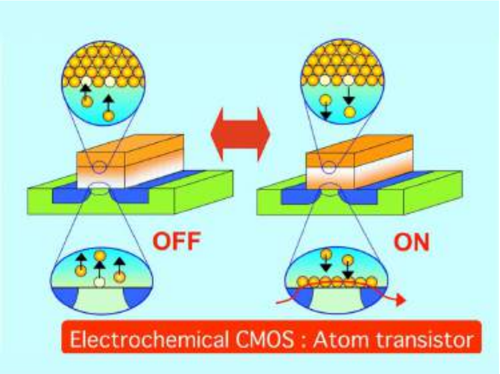

Fig. 1 Schematics of the atom transistor

Presentation Title:

Artificial Synapses Realized by Atomic Switch Technology

Authors:
°Tohru Tsuruoka[1], Takeo Ohno[1,2], Alpana Nayak[1,3], Rui Yang[1,4], Kazuya Terabe[1], Tsuyoshi Hasegawa[1,5], James K. Gimzewski[1,6], and Masakazu Aono[1]

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Abstract:

In addition to bi-resistive switching, the unique characteristics of the atomic switch are conductance quantization and synaptic behaviors. The atomic switch synaptic plasticity when the device conductance varies depending on the history of the switching events and the bias voltage applied at the time. We demonstrated that sulfide-based gap-type atomic switches could emulate two types of memorization in the human brain through the use of input pulse repetition time: short-term memory (STM) and long-term memory (LTM) modes [3]. This plasticity is influenced by the presence of air or moisture and depends on temperature [4]. An $Ag/Ta_2O_5/Pt$ atomic switch also exhibits the STM and LTM behaviors under the application of input voltage pulses with varied repetition times [5]. The transition between STM and LTM over a wide time scale can also be achieved using the transport of oxygen vacancies in a $Pt/WO_{3-x}/Pt$ device [5].

Our results show that individual atomic switches enable a new functional element suitable for the design of neural systems that can work without the poorly scalable software and preprograming employed in current CMOS-based neural networks. These artificial synapses will contribute to the achievement of next-generation neural computing systems.

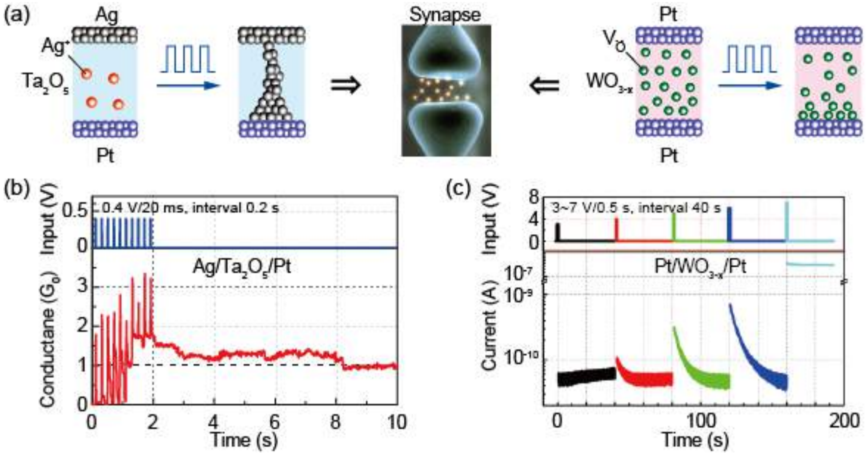

Fig. 1 (a) Atomic switches work as an artificial synapse. (b) An $Ag/Ta_2O_5/Pt$ device shows LTM under high input repetition rates. (c) A $Pt/WO_{3-x}/Pt$ device shows the transition from STM to LTM depending on input strength.

[1] Ohno et al., Nature Mater. **10**, 591 (2011), [2] Nayak et al., Adv. Funct. Mater. **22**, 3606 (2012), [3] Tsuruoka et al., Nanotechnology **23**, 435705 (2012), [4] Yang et al., ACS Nano **6**, 9515 (2012); Nanotechnology **24**, 384003 (2013).

Presentation Title:

Atom Switches for Neuroarchitectonics

Authors:
°James K. Gimzewski[1,2,3], Adam Z. Stieg[2], Renato Aguilera[3], Kelsay Scharnhorst[3], Eleanor C. Demis[3], Henry O. Sillin[3], Eric J. Sandouk[3], Audrius V. Avizienis[3], and Masakazu Aono[1]

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Abstract:

Atomic switch-based devices are a base configuration for neuromorphic logic and memory. They are CMOS compatible and are comprised of directed self-assembled wiring with nanoscale synaptic-like junctions[1]. The atomic switch is an electroionic circuit exhibiting multi-state switching and volatile memory capabilities similar to biological synapses through a bias-driven filamentary switching mechanism. The Atomic Switch Network (ASN) is a radically divergent architecture in which the individual atomic switches are interconnected in a network inspired by neuronal mechanisms in the brain[2,3]. Operation of atomic switch networks leads to a class of emergent behaviors (constantly reconfiguring energetic potential, power law dynamics, and distributed spatiotemporal switching events). The distributed dynamics of the ASN make it a hardware candidate for reservoir computing, (RC). We will discuss ASN's from the single switch level up to network operation for RC. Finally we will provide an outlook of their operation as hybrid devices and also as three-dimensional brain-like embodiments.

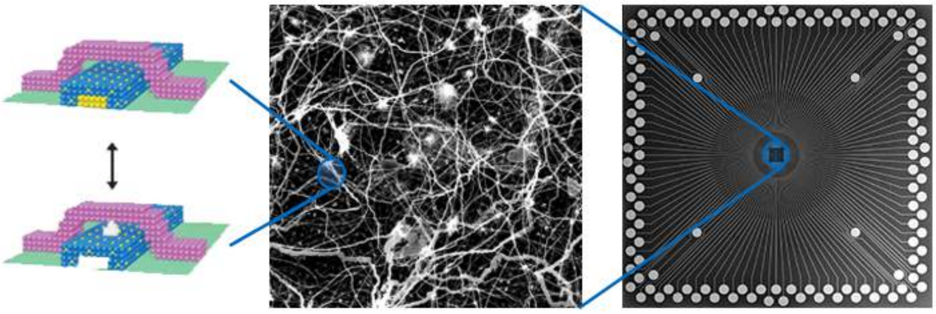

Fig. 1 (Left) Schematic representation of a single atomic switch. (Center) Scanning electron microscope image of an ASN device comprising individual atomic switch elements embedded within a network of highly interconnected silver wires. (Right) Self-organized nanowires integrated into a CMOS-compatible device platform with 120 electrodes.

References:
[1] E. Demis, R.C Aguilera, H.O. Sillin, E.J. Sandouk, K. Scharnhorst, M. Aono, A.Z. Stieg and J.K Gimzewski. Nanotechnology **26**, 204003 (2015).
[2] J.K. Gimzewski, A.Z. Stieg, V. Vesna, *Handbook of Science and Technology Convergence* DOI 10.1007/978-3-319-04033-2_74-1 (2015).
[3] E. Demis, R.C Aguilera, K. Scharnhorst, M. Aono, A.Z. Stieg, J.K Gimzewski, *Japanese Journal of Applied Physics* **55,** 1102B (2016).

Presentation Title:

Emerging Functionality of Neuromorphic Networked Structures

Authors:
°Tomonobu Nakayama[1,2], Rintaro Higuchi[1], Yoshitaka Shingaya[1], Zdenka Kuncic[3], James K. Gimzewski[1,4], and Masakazu Aono[1]

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Abstract:

As an emerging functionality of neruromorphically networked structures, we report associative memorization, which is considered to be a promising functionality towards future computation. In this presentation, we discuss three important features of the networks, such as a “small-world” property, existence of long-term/short-term memorization behaviors and 1/f characteristics, through our nano- and macro-scale electrical measurements, and finally leading us to propose brain-type computation for future information technology.

We prepared inorganic/organic neuromorphic nanowire networks of doped poly-aniline nanowires (PANI-NWs) and sliver nanowires (Ag-NWs) by wet-chemical methods and by drop-casting or spin-coating them onto insulating substrates such as mica and SiO_2. In the case Ag nanowires, about 1-nm thick insulating layer of polyvinylpyrrolidone (PVP) was formed over the surface of each nanowire. Then, we used multiple-probe scanning probe microscope (MP-SPM) [1] and related techniques to measure electrical properties of the PANI- and Ag-NW networks.

The resistances measured for the PANI nanowire networks indicated “small-world” characteristics of the networks [2]. The Ag nanowire network was highly resistive (OFF-state) because the thin insulating PVP layer prevented metal to metal contacts between Ag nanowires. Interestingly, the resistance of the Ag-NW network was orders of magnitude lowered by an application of appropriate voltages across the network. The low-resistance state (ON-state) returned to the OFF-state after some retention time, indicating the network itself can memorize information to some extent. Also, the Ag nanowire networks show 1/f fluctuation as a result of ON-OFF switching phenomena and dynamic fluctuation of current paths as confirmed by both experiments and simulations. We propose and demonstrate that the above features can be devised to associative memory devices for future computation.

References:

[1] T. Nakayama, O. Kubo, Y. Shingaya, S. Higuchi, T. Hasegawa, C.-S. Jiang, T. Okuda, Y. Kuwahara, K. Takami, and M. Aono, “Development and Application of Multiple-Probe Scanning Probe Microscopes”, Advanced Materials **24**, 1675-1692 (2012).

[2] D. J. Watts and S. H. Strogatz, “Collective dynamics of ‘small-world’ networks”, Nature **393**, 440-442 (1998).

Presentation Title:

Atomistic Simulations for Understanding Microscopic Mechanism of Atomic Switch

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Abstract:

We performed simulations aiming at obtaining atomistic understanding on the behaviors of atomic switches. As an example, we examined Cu/amorphous-Ta_2O_5/Pt heterostructure [1]. Simulations within the density functional theory (DFT) reveals that single Cu chains in Ta_2O_5 cannot work as conductive filaments (CFs), while Cu nanowires with a diameter of three atoms or larger can work as CFs. The stability of the Cu nanowires has been checked by ab initio molecular dynamics. We also discuss the difference in the atomistic features between Cu/Ta_2O_5 and Pt/Ta_2O_5 interfaces: In the former, considerable number of interface Cu atoms tend to migrate to the amorphous Ta_2O_5 layer, while similar behavior is not seen in the latter [2].

In addition, we describe our attempt to construct simplified neural network (NN) interatomic potentials [3] for simulations of Cu migration behavior in amorphous-Ta_2O_5 with achieving computation speed and reliability simultaneously. The structures and data for the NN training are obtained using DFT. The pathways and barrier energies for Cu diffusion calculated using the NN potential agree well with those obtained from DFT calculations [4]. This part of the present works was partly supported by the Support Program for Starting up Innovation hub from Japan Science and Technology Agency (JST), and CREST-JST, Japan.

References:

[1] B. Xiao, T. Gu, T. Tada, and S. Watanabe, J. Appl. Phys. **115**, 034503 (2014).
[2] B. Xiao and S. Watanabe, ACS Appl. Mater. Interfaces **7**, 519 (2015).
[3] J. Behler and M. Parrinello, Phys. Rev. Lett. **98** (2007) 146401.
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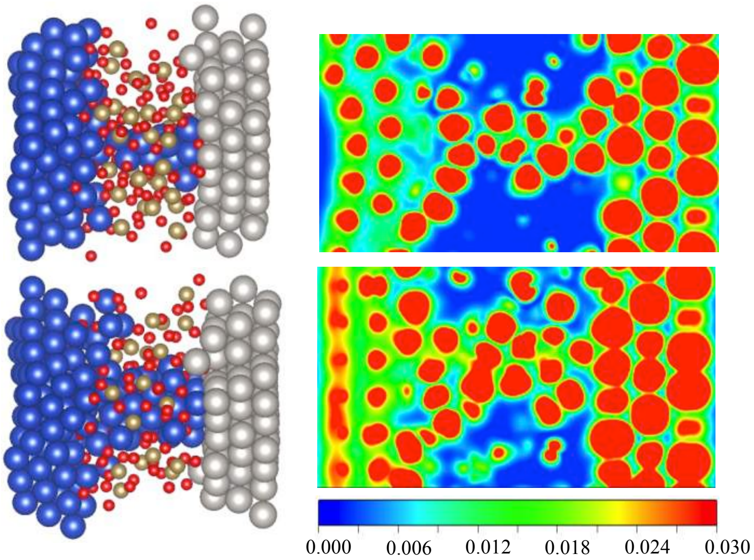

Fig. 1 (Left) Schematics of Cu conductive filaments obtained in our simulations. (Right) Corresponding local density of states At the Fermi level.

Presentation Title:

Atomic Switch Based Decision Making

Authors:
°Song-Ju Kim[1], Tohru Tsuruoka[1], Tsuyoshi Hasegawa[1,2], Masashi Aono[3,4], Kazuya Terabe[1], and Masakazu Aono[1]

Affiliation:
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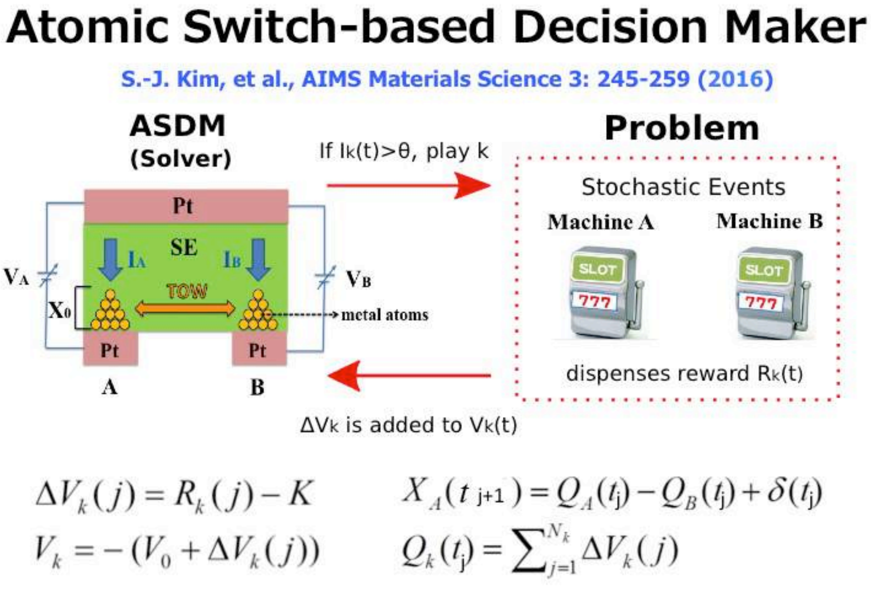
Abstract:

We considered a popular decision-making problem studied in the context of reinforcement learning, the multi-armed bandit problem (MAB); the problem of finding, as accurately and quickly as possible, the most profitable option from a set of options that gives stochastic rewards. These decisions are made as dictated by each volume of precipitated metal atoms, which is moved in a manner similar to the fluctuations of a rigid body in a tug-of-war game.

The "tug-of-war (TOW) dynamics" of the atomic switch-based decision maker (ASDM) exhibits higher efficiency than conventional reinforcement-learning algorithms. We show analytical calculations that validate the statistical reasons for the ASDM to produce such high performance, despite its simplicity. The proposed scheme will open up a new direction in physics-based analog-computing paradigms, which will include such things as "intelligent nanodevices" based on self-judgment.



Atomic Switch-based Decision Maker

S.-J. Kim, et al., AIMS Materials Science 3: 245-259 (2016)

$$\Delta V_k(j) = R_k(j) - K \qquad X_A(t_{j+1}) = Q_A(t_j) - Q_B(t_j) + \delta(t_j)$$

$$V_k = -(V_0 + \Delta V_k(j)) \qquad Q_k(t_j) = \sum_{j=1}^{N_k} \Delta V_k(j)$$

References:
[1] S. -J. Kim, et al., AIMS Materials Science **3**, 245-259 (2016).
[2] S. -J. Kim, M. Aono, & E. Nameda, New J. Phys. **17**, 083023 (2015).
[3] M. Naruse S. -J. Kim, et al., Sci. Rep. **5**, 13253 (2015).
[4] S. -J. Kim, M. Naruse, M. Aono, M. Ohtsu & M. Hara, Sci. Rep. **3**, 2370 (2013).

Presentation Title:

Nanoionic Devices for Physical Property Tuning and Enhancement

Authors:

°Takashi Tsuchiya[1], Tohru Tsuruoka[1], Kazuya Terabe[1], and Masakazu Aono[1]

Affiliation:

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Abstract:

Nanoionic devices have been developed to generate novel functions overcoming limitations of conventional materials synthesis and semiconductor technology.[1,2] Various physical properties can be tuned and enhanced by local ion transport near the solid/solid interface. Two electronic carrier doping methods can be used to achieve extremely high-density electronic carriers: one is electrostatic carrier doping using an electric double layer (EDL); the other is electrochemical carrier doping using a redox reaction. Atomistic restructuring near the solid/solid interface driven by a DC voltage, namely, interface nanoarchitechtonics, has huge potential (Figure 1). For instance, the use of EDL enables high-density carrier doping in potential superconductors, which can hardly accept chemical doping, in order to achieve room-temperature superconductivity. Optical bandgap and photoluminescence can be controlled for various applications including smart windows and biosensors. *In situ* tuning of magnetic properties is promising for low-power-consumption spintronics.

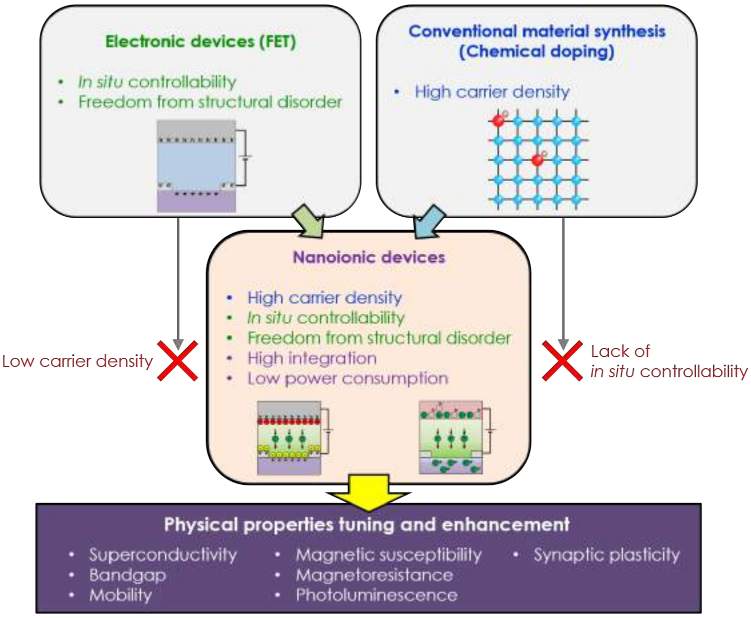

Fig. 1 Schematic illustration of comparing electronic devices, conventional material synthesis, and nanoionic devices.

References:

[1] T. Tsuchiya *et al.* Jpn. J. Appl. Phys. **55** (2016) 1102A4.
[2] K. Terabe *et al.* Nanoscale **8** (2016) 13873.

International Symposium on
Atomic Switch
2017

Poster Presentation

P01: Presentation Title:

Demonstration of Video encoding using atomic-switch based FPGA

Authors:
°T. Sakamoto[1], M. Tada[1], M. Miyamura[1], X. Bai[1], Y. Tsuji[1], R. Nebashi[1], A. Morioka[1], N. Banno[1], K. Okamoto[1], N. Iguchi[1], H. Hada[1], and T. Sugibayashi[1]

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Abstract:

We demonstrate the video encoding using atomic-switch based FPGA. A 64x64 programmable-logic cell array includes a 9.2-Mbit atomic switch as the routing switch and configuration memory of LUT (Fig. 1). Each cell has two 4-input LUT and a total number of LUTs is 8.2k which correspond to 20k-ASIC gate.

The encoding algorism is implemented on atomic-switch FPGA. We develop a mapping tools, where the configuration data is generated from RTL code of the encoding algorism. The video data is introduced and encoded in the atomic-switch based FPGA. Then, the encoded stream data is decoded by using PC, showing the video image on the display (Fig. 2). FPGA performs 30 flames/sec of 8bit-gray scale video image with 640x480 pixels.

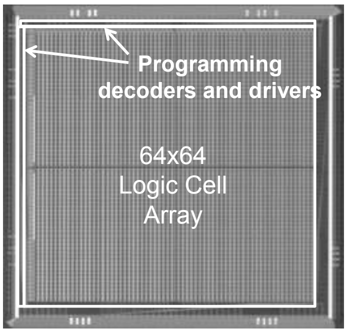

Fig. 1 64x64 atomic-switch based FPGA.

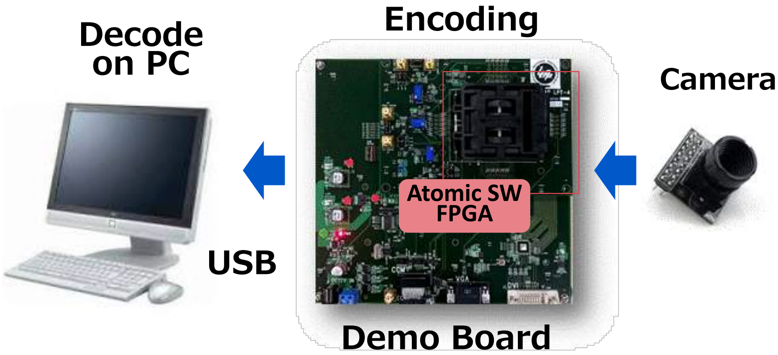

Fig. 2 Demonstration flow.

P02: Presentation Title:

An Evaluation of Single Event Effect by Heavy Ion Irradiation on Atom Switch ROM / FPGA

Authors:
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Abstract:

"Normally-off computing" featuring a next generation non-volatile memory, which enables to shut the power down whenever not being used, is one of the most promising methodologies to reduce the power consumption in LSI and electronic devices [1]. In this work, we investigate a radiation tolerance of the new memory to achieve "Normally-off computing" in aerospace. NanoBridge (a.k.a. Atom switch) as the nonvolatile memory/switch is subject to be irradiated in a radiation facility, and SEU cross-section against high LET heavy ion was evaluated.

The radiation tolerance of both Atom switch ROM and CAS (complementary atom switch) FPGA were evaluated by using the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) in the National Institutes for Quantum and Radiological Science and Technology (QST). Atom switch ROM and CAS FPGA were initially developed by LEAP (Low-power electronics Association & Project) and now NEC continues to develop them as NanoBridge®. The chips were irradiated by Xe ion. LET (Linear energy transfer) of Xe was calculated to be 68.9 [MeV/(mg/cm^2)] at Si surface [2].

No SEU (Single Event Upset or bit flip) was observed through experiment. Atom switch was programmed for either ON or OFF state and validated before and after the radiation test by LSI tester. Since actual cell area of Atom switch is 1.5×10^{-11} [cm^2], about 19 or 122 particles were expected to hit somewhere in Atom switches on ROM or FPGA respectively. Figure 1 shows estimated SEU cross section against Xe ion which has 69.8 [MeV/(mg/cm^2)] in LET. In-house Cf-252 data [3] was also plotted in 30 [MeV/(mg/cm^2)] in Fig. 1. It was revealed that SEU cross sections against heavy ions are much smaller than the Atom switch cell itself irrespective of voltage conditions or cell states.

[1] K. Ando, FED Journal, vol. **12**, no. 4, pp. 89-95, 2001.
[2] http://www.srim.org/
[3] K. Takeuchi et al., poster material, MEWS28, Oct., 2015

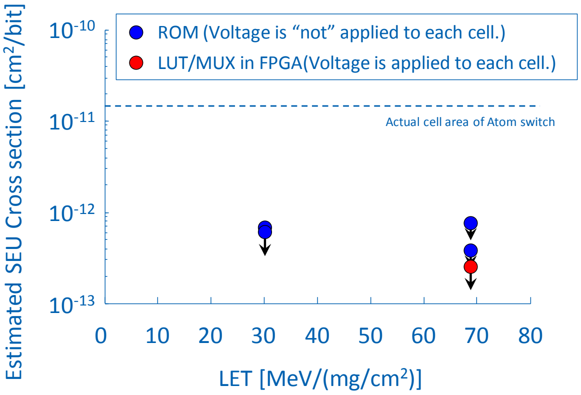

Fig. 1 Estimated SEU cross-section and actual cell area of atom switch

P03: Presentation Title:

Solid-Polymer-Electrolyte-Based Atomic Switches

Authors:
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Abstract:

We have demonstrated that the atomic switch operation can be realized using a solid polymer electrolyte (SPE). Ag/SPE/Pt devices, in which an Ag-salt incorporated polyethylene oxide (Ag-PEO) film is used as SPE, showed bipolar resistive switching with a high ON/OFF resistance ratio under bias voltage sweeping [1]. The observed switching behavior is found to result from formation and dissolution of an Ag metal filament inside the SPE film, as in the case of inorganic solid-electrolyte-based atomic switches. We subsequently succeeded in fabricating a cross-point structured cell on a plastic substrate using an inkjet-printed Ag-PEO film, and obtained stable switching characteristics when the substrate was bent [2]. This result indicates that the SPE-printed atomic switch could be a promising candidate for flexible switch/memory applications.

Recently, successful *in situ* optical microscopy and *ex situ* SEM observations were made of conducting filament growth behavior in a planar structure [3]. It was found that the filament growth is significantly influenced by the properties of the polymer matrix, such as its crystallinity and ionic conductivity, which are determined by the addition of metal salts, and by changing experimental parameters such as the compliance current and the voltage sweep rate. Moreover, highly reproducible conductance quantization was demonstrated in an Ag/PEO/Pt structure, and a comparison between the experimental and theoretical results provides additional insight that allows a fundamental understanding of resistive switching behavior, as well as quantized conductance variations.

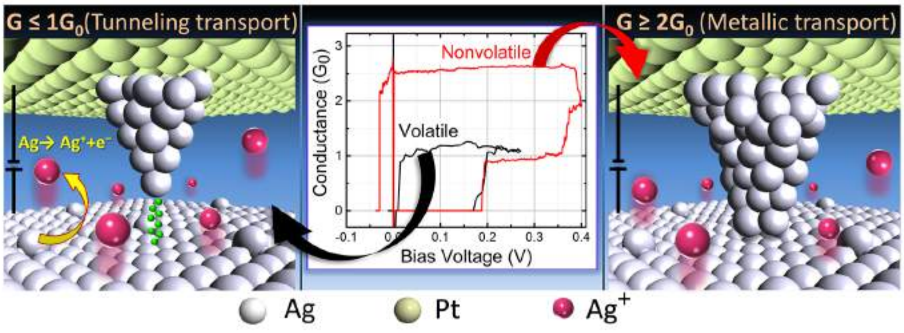

Fig. 1 Conductance quantization observed in a PEO-based atomic switch

[1] Wu et al., Adv. Funct. Mater. **21**, 93 (2011).
[2] Mohapatra et al., AIP Ad. **2**, 022144 (2012); J. Mater. Chem. C **3**, 5715 (2015).
[3] Krishnan et al., Adv. Mater. **28**, 640 (2016); Nanoscale **8**, 9009 (2016); Jpn. J. Appl. Phys. **55**, 06GK02 (2016).
[4] Krishnan et al., Adv. Funct. Mater., published online (2017); Jpn. J. Appl. Phys. (in press).

P04: Presentation Title:

Psychological Memorization Model Demonstrated by Atomic Switches

Authors:
°Takeo Ohno[1,2,4], Tsuyoshi Hasegawa[3,4], Tohru Tsuruoka[4], Kazuya Terabe[4], Alpana Nayak[4,5], James K. Gimzewski[4,6], and Masakazu Aono[4]

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Abstract:

Atomic switch is generally known as nanoionics switching memory devices that operate by controlling the movement of metallic cations/atoms and their reduction/oxidation processes to make conductive paths. At the beginning stage of this research, an ON/OFF switching operation with quantized conductance was reported [1]. After that, we have found that atomic switches possess novel characteristics, such as learning ability depending on the history of input signals [2,3] and time-dependent operation similar to that of a biological synapse [4–6]. In addition, several fascinating behaviors, psychological human memories, have been demonstrated by atomic switches. The atomic switch exhibits time-dependent electrical conductance, which enables a formation of the human memory such as sensory memory, short-term memory and long-term memory [4,7]. On the basis of these results, multi-store memorization model and forgetting curve of human memory in psychology were demonstrated. These novel behaviors of atomic switches will enable the development of beyond von-Neumann architecture. Recently, in order to improve the psychological and neuromorphic operation, we are fabricating a gapless-type atomics switch with a nanometer-thick metallic oxide film as an ionic conductor [8].

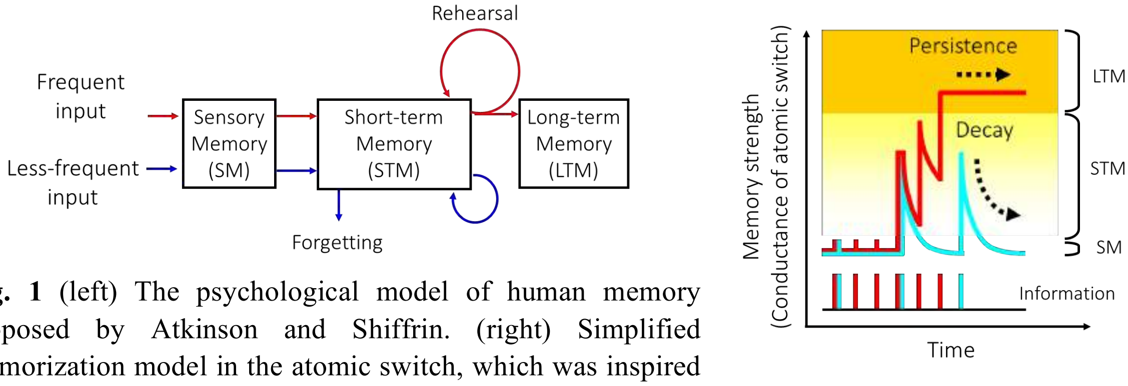

Fig. 1 (left) The psychological model of human memory proposed by Atkinson and Shiffrin. (right) Simplified memorization model in the atomic switch, which was inspired by the multistore model.

[1] K. Terabe et al., *Nature* **433**, 47–50 (2005).
[2] T. Hasegawa et al., *Advanced Materials* **22**, 1831–1834 (2010).
[3] T. Hasegawa et al., *Applied Physics A* **102**, 811–815 (2011).
[4] T. Ohno et al., *Nature Materials* **10**, 591–595 (2011).
[5] A. Nayak et al., *Advanced Functional Materials* **22**, 3606–3613 (2012).
[6] T. Tsuruoka et al., *Nanotechnology* **23**, 435705 (2012).
[7] T. Ohno et al., *Applied Physics Letters* **99**, 203108 (2011).
[8] T. Ohno et al., *Applied Physics Letters* **106**, 173110–1–4 (2015).

P05: Presentation Title:

Neuromorphic Atomic Switch Networks for Natural Computing

Authors:
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Abstract:

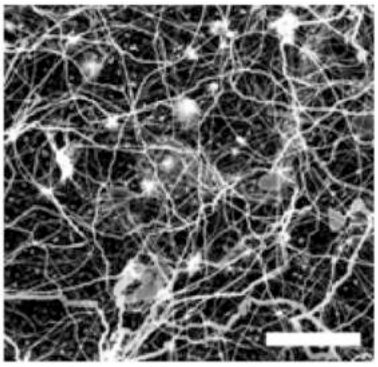

Fig. 1 SEM image of an atomic switch network (Scale bar = 50 μm)

Attempts to realize a low-power, dynamically complex system for computation become imperative as the limits of CMOS technology are approached. Biological brains exist as an inspiring natural system that hold enormous computational power via information processing, storage and logic while only requiring small amounts of energy. Utilizing nanoarchitectonics, or a mixture of top-down and bottom-up methods, we fabricate highly interconnected atomic switch networks (ASNs) that structurally resemble neuronal networks (Figure 1)[1,2]. Individual elements consist of a metal insulator metal (MIM) junction that switches ON/OFF with applied bias. These purpose-built systems exhibit the collective interaction of nonlinear circuit elements with one another, leading to behaviors more complex than those of individual elements.[3] Emergent behaviors include spatially and temporally distributed switching, long and short term memory, and nonlinear transformation of information into higher dimensional space. These emergent behaviors make ASNs suitable for alternative natural computing paradigms, or computing inspired by nature.[4] Specifically, our group specializes in the experimental implementation of reservoir computation using the ASN as a complex physical platform for this paradigm.[5]

References:

[1] A.V. Avizienis, C. Martin-Olmos, H.O. Sillin, M. Aono, J.K Gimzewski and A.Z. Stieg. Crystal Growth & Design **13**, 465 (2013).

[2] E.C. Demis, R. Aguilera, H.O. Sillin, K. Scharnhorst, E.J. Sandouk, M. Aono, A.Z. Stieg and J.K. Gimzewski. Nanotechnology **26**, 204003 (2015).

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P06: Presentation Title:

Investigation of dynamic phenomena in polymer-coated Ag nanowire network

Authors:
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Abstract:

Neuromorphic circuits composed of electronic devices are required to realize brain-like information processing such as learning and recognition which are observed in a biological system. “Atomic switches” have attracted attention as the materials for mimicking the functions of synapses.[1,2] Recently atomic switch networks have been studied for generating the neuromorphic structure and function by interconnecting numerous atomic switches each other.[3] However the phenomena occurring in the network have yet to be revealed. In this study, we analyze the fluctuation observed in the polymer-coated Ag nanowire (pc-AgNW) network, one of the atomic switch networks, for understanding the network dynamics.

Scanning electron microscopy (SEM) revealed that AgNWs formed a random network structure on the substrate (Fig. 1a). The spontaneous fluctuation in output current was observed when the constant voltage was applied to pc-AgNW network. Figure 1b shows a typical power spectral density (PSD) of current signal obtained by fast Fourier transform. The PSD followed the inverse of frequency, which behavior is well-known as 1/f noise. It was found that the exponent of 1/f (slope of PSD) changes with the conductance of network, and expected that this behavior should correlate to the network dynamics.

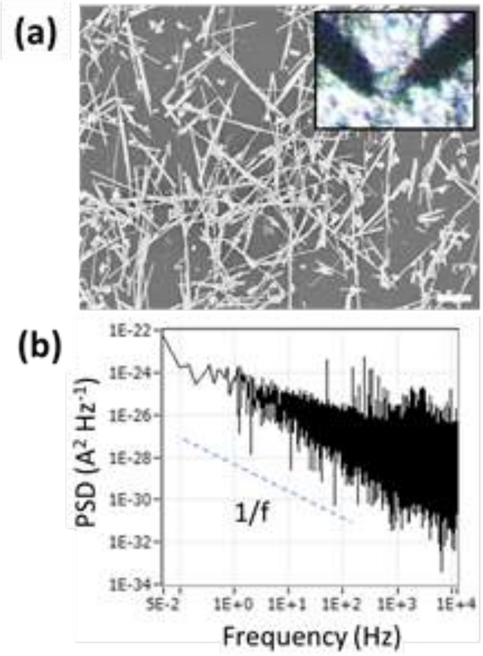

Fig. 1 (a) SEM image of AgNW network. The inset shows optical micrograph of double probes and sample. Scale bar = 10 mm. (b) PSD of measured current.

References:
[1] K. Terabe *et al.*, Nature **433**, 47 (2005).
[2] T. Ohno *et al.*, Nat. Mater. **10**, 591 (2011).
[3] A. V. Avizienis et al., PLoS One **7**, e42772 (2012).

P07: Presentation Title:

Conduction through Thermosensitive Networks

Authors:
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Abstract:

A gel formed in surfactant mixture possesses entangled networks. An incorporation of polymer into this gel retains these entangled networks. This incorporation of polymer in surfactant mixture enhances rheological properties of networks formed by surfactant mixtures only: like viscosity, elasticity and relaxation time as confirmed by rheological measurements. The rheological property of both gels is dependent on concentration of components, temperature. The polymer-incorporated gel possesses enhanced conducting properties. Measurements show that the conductivity is sensitive to temperature, concentration of components. Interesting temperature dependent potential and current distribution pattern were observed through the network in the matrix of gel. These temperature dependent pattern were assigned to the temperature induced structural transformation in the gel.

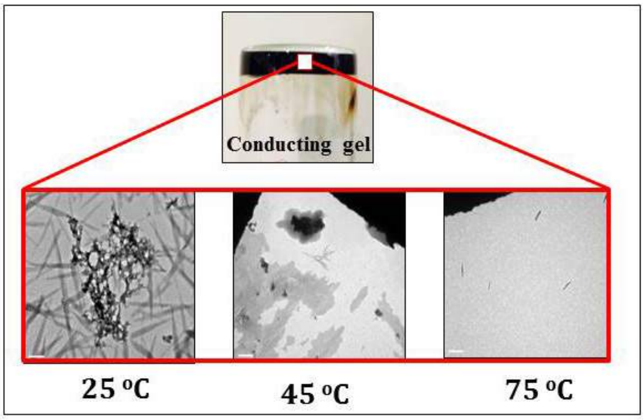

Fig. 1 Self-Standing Conducting Gel (above), and TEM images of the gel at different temperatures (below).

P08: Presentation Title:

Functionalized PANI Network Conductor towards Future Computation

Authors:
°Li Qiao[1,2], Rintaro Higuchi[2], Yoshitaka Shigaya[2], Yasuko Kato[2], Keiko Tanaka[2], and Tomonobu Nakayama[1,2]

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Abstract:

The memristive resistor has been a long time candidate for the artificial neural network as it has similar short-term plasticity and long-term potentiation as neuro synapse[1]. Recent works on resistive switching access memory[2] give the confidence to achieve computation on the memristive device. Most efforts have been worked on regular resistor network which needs complex lithographic technology[2]. Here we propose a simple approach with functionalized polyaniline complex network. PANI is a widely used conductive polymer which is flexible and stable in the air but does not have switching behavior. 1/f noise measurement shows PANI network is scale-free, which has also been found in our brain[3]. We firstly functionalized PANI with gold nanoparticles(GNP) to form GNP/PANI fibers. GNP/PANI film has been proved to have bistable switching behavior. Our I-V measurement on GNP/PANI nanofibers shows similar bistable switch behavior. Test of the memristive efficiency on our complex network is on the going.

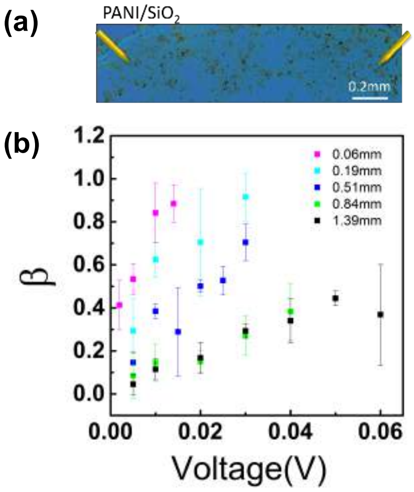

Fig. 1 (a) Optical image of smaple with two probes. (b) 1/f noise measurent result versus volatge with different probe distances.

References:

[1] J. Joshua Y., Dmitri B. S. & Duncan R. S. Memristive devices for computing. *Nature Nanotec.* **8**, 13–24 (2013).

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[3] Victor M. E. et al. Scale-free brain functional networks. *Phys. Rev. Lett.* **94**, 018102 (2005).

P09: Presentation Title:

MP-AFM Measurement of Metal and Polymer Nanowires as Basic Components of Neuromorphic Network System

Authors:
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Abstract:

Neuromorphic network systems are fascinating research target, since they have potential to realize huge parallel computing with low power consumption. We have constructed network system with nanomaterials such as polyaniline nanofibers or polymer coated Ag nanowires (Fig.1) and electrical property of the network system was investigated. To understand electrical property of the network, measurement of electrical property of each component such as single nanowire and single nanowire junction is very important. We applied multiple-probe atomic force microscope (MP-AFM) for that measurement. The MP-AFM which we have developed, has independently driven four probes and four-probe electrical measurement is possible at designated positions with nanoscale precision on a sample. Figure 2 shows overlapped AFM image of Ag nanowires obtained simultaneously with four probes. Four probe electrical measurements were carried out with probe configuration as shown in the figure. Slightly larger electrical resistivity than that of bulk Ag was obtained. Electrical properties of single nanowire junctions were also observed with MP-AFM.

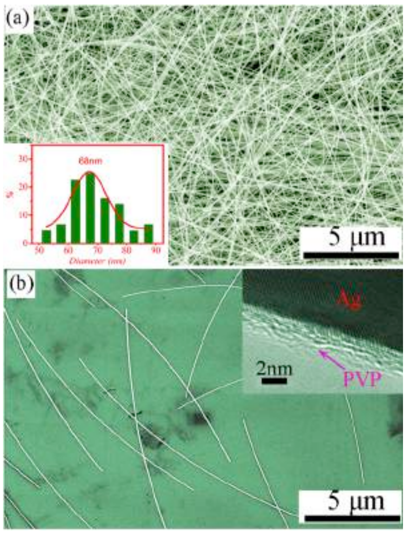

Fig. 1 (a) SEM image of Ag nanowire network. (b) SEM imgae of isolated Ag nanowires on SiO_2 substrate.

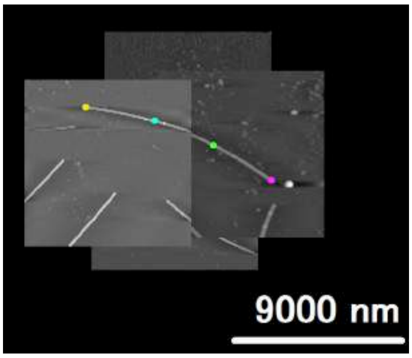

Fig. 2 AFM image obtained with four probes simultaneously. Four dots show probe position for four probe electrical measurement.

P10: Presentation Title:

‘Tug of War’ Devices for Interconnection of Artificial Synapses

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Abstract:

Neuromorphic systems are an alternative for common Von Neumann computers as they should one day achieve a higher processing power on succeeded in demonstrating the function using a solid-state three-terminal device [2], based on a Ag_2S gap-type atomic switch, as shown in Fig. 1. In the ‘Tug of War’ operation, the growth of the right Ag filament pulls back the left Ag filament to the center Ag_2S electrode. This operation becomes possible when the total volume of Ag in the system is limited.

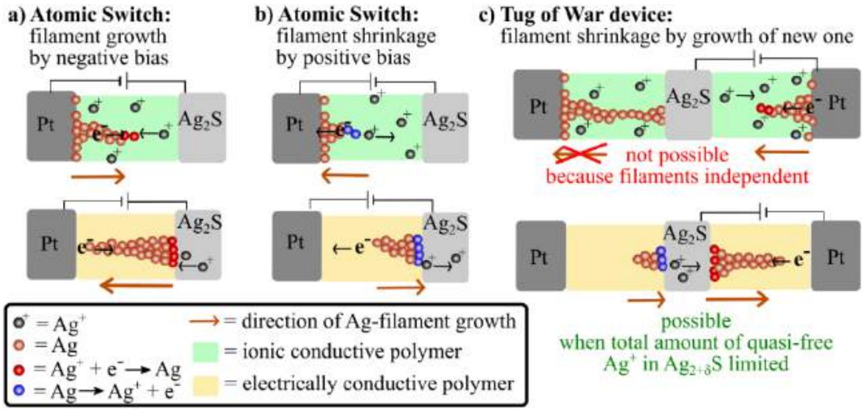

Fig. 1 Schematic of common atomic switches and the special Tug of War processing. a) A filament grows when a bias is applied. b) in common atomic switches, filaments only shrink when a bias of opposite sign is applied. c) In Tug of War operation, however, a filament will shrink, when a new filament is grown towards the second counter electrode. This is similar to neuronal connections being weakened when an opposing information is learned.

‘Tug of War’ elements are promising candidates for CMOS-free neuromorphic networks, however the first devices showed problems such as cluster formation within the gap-material. We found that this can be avoided by using electronically conductive materials with low ionic conductivity, such as π-conjugated polymers, independent of being n- or p-type [3]. The main goal of this study is to make these devices ready for implementation in the first CMOS-free networks. For this we optimize the gap-material and sample design and do the first systematic data collection for this new technology. We analyzed different π-conjugated polymers, such as the n-type polymer ActiveInk N2200, and the p-type polymers P3EHT and P3HT showing much lower ion conductivity compared to the previously used PEO+BTOE. P3HT with very low chain length is especially promising for this application. Furthermore, we added a channel structure to our device design to better control the electric field and by this the direction of Ag-filament growth within the gap-material. The device fabrication was mainly done using electron beam lithography and electron beam deposition. The polymers are deposited by spin coating. In the experiments, we applied a bias voltage to the counter electrodes using an IV measurement system and switch the ‘Tug of War’ resistive switch alternatingly between the two counter electrodes as schematically depicted in Fig. 1. The technology will be utilized when ‘Tug of War’ is implemented in first non-hybrid CMOS-free neuromorphic systems.

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[2] C. Lutz, T. Hasegawa, T. Chikyow, *Nanoscale* **21**, 613 (2016).
[3] C. Lutz, T. Hasegawa, T. Tsuchiya, C. Adelsberger, R. Hayakawa, T. Chikyow, submitted to *JJAP*.

P11: Presentation Title:

Study of Atom Diffusion in Amorphous Structures with Neural Network Potentials

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Abstract:

Theoretical study of metal atom diffusion in amorphous insulator layers is important to understand the mechanism of atomic switches. Reliable computational methods like density functional theory (DFT) are capable of clarifying the atomic diffusion behavior, but require heavy computation.

In this study, we demonstrate that two methods based on the neural network (NN) interatomic potential [1] can be used to study the atomic diffusion in amorphous materials. The first one is the simplified NN potential that focuses on only diffusing atoms. We have investigated the single Cu atom diffusion paths and activation energies in amorphous Ta_2O_5 (*a*-Ta_2O_5) with this method. The second one is the high-dimensional NN potential [1]. Using this method together with nudged elastic band method and molecular dynamics, we have characterized Li diffusion in amorphous Li_3PO_4. Figures 1 and 2 show examples of calculation results obtained using the first and second methods, respectively. From these figures, we can see that both the first and second NN potential methods give good agreement with DFT calculations.

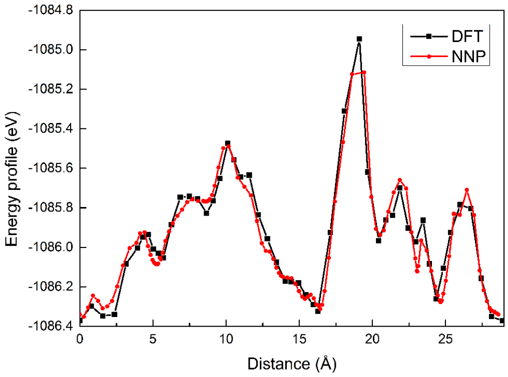

Fig. 1 Energy profile along a Cu diffusion path in amorphous Ta_2O_5 calculated by DFT and simplified NN potential.

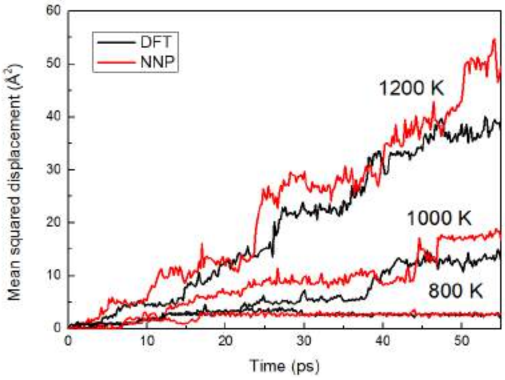

Fig. 2 Time evolution of mean square displacement of Li atoms in amorphous Li_3PO_4 in molecular dynamics simulation.

[1] J. Behler and M. Parrinello, Phys. Rev. Lett. **98**, 146401 (2007).

P12: Presentation Title:

Effects of the composition of Ta_2O_5 films on the resistive switching properties of Ta_2O_5 based atomic switches

Authors:
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Abstract:

Resistive switching memory based on cation migration in a thin oxide film is considered as a good candidate for next generation, non-volatile memory applications, thanks to their promising properties such as high speed, low power consumption, and high compatibility with CMOS technologies, ensured by a basic metal/insulator/metal (MIM) structure [1]. Because of its similarity to the operating mechanism of 'gap-type atomic switch' [2], cation-migration- based MIM cells can be referred to as 'gapless-type atomic switch' [3]. Here, we present how the oxide film composition affects the switching behavior, in relation to moisture absorption from the ambient surrounding [4,5] and the cell configurations such as the electrode material.

Cu/Ta_2O_5/metal cells were investigated, in which the Ta_2O_5 film was formed by electron-beam deposition (EB) or RF sputtering (SP). XRD and XRR revealed an amorphous nature for both films and a lower film density in the EB film. FT-IR spectra exhibited the existence of peroxo species and a large number of absorbed water in the EB film. XPS analyses revealed oxygen rich composition for both films and a higher O/Ta ratio in the EB film.

Figure 1 shows the variation of the SET (from the OFF state to the ON state) and RESET (form the ON state to the OFF state) voltages with changes in the ambient atmosphere, measured for Cu/Ta_2O_5/Pt cells. The SET process corresponds to the formation of a Cu filament by precipitation on the Pt electrode, while the RESET process is attributed to the dissolution of the filament due to oxidation of Cu assisted by Joule heating [6]. The decreased SET and RESET voltages in vacuum of the cell with the EB film can be explained by enhanced Cu dissolution and subsequent ion migration in a hydrogen-bond network of the Ta_2O_5 matrix, resulting from formation of hydroxylated tantalum oxides (Ta-OH) and chemisorption of water on them. This finding is very important in understanding and controlling the performance of oxide-based atomic switches.

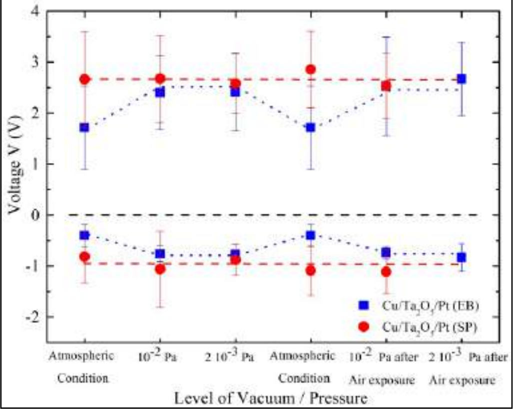

Fig. 1 SET and RESET voltages of Cu/ Ta_2O_5/Pt cells for different ambient pressures.

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P13: Presentation Title:

Electrical-Pulse-Induced Resistivity Modulation in Pt/TiO_{2-d}/Pt Multilayer Device Relevant to Nanoionics-Based Neuromorphic Function

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Abstract:

Resistivity modulation behavior in Pt/TiO_{2-d}/Pt multilayer devices was investigated relevant to nanoionics-based neuromorphic function. The current relaxation behavior, which corresponds to short-term memorization and long-term memorization in neuromorphic function, was analyzed by using electrical pulses. The memorizations are shown in figure 1 (a) and (b).

In contrast to the huge difference of ionic conductivity for bulk crystal materials of TiO_2 and WO_3, the difference in the relaxation behavior was small. Rutherford backscattering spectrometry and hydrogen forward scattering spectrometry evidenced that 5.6at% of protons are incorporated in the TiO_2 thin film. The result indicated that the neuromorphic function in TiO_2-based devices is caused by extrinsic proton transport presumably through grain boundary.

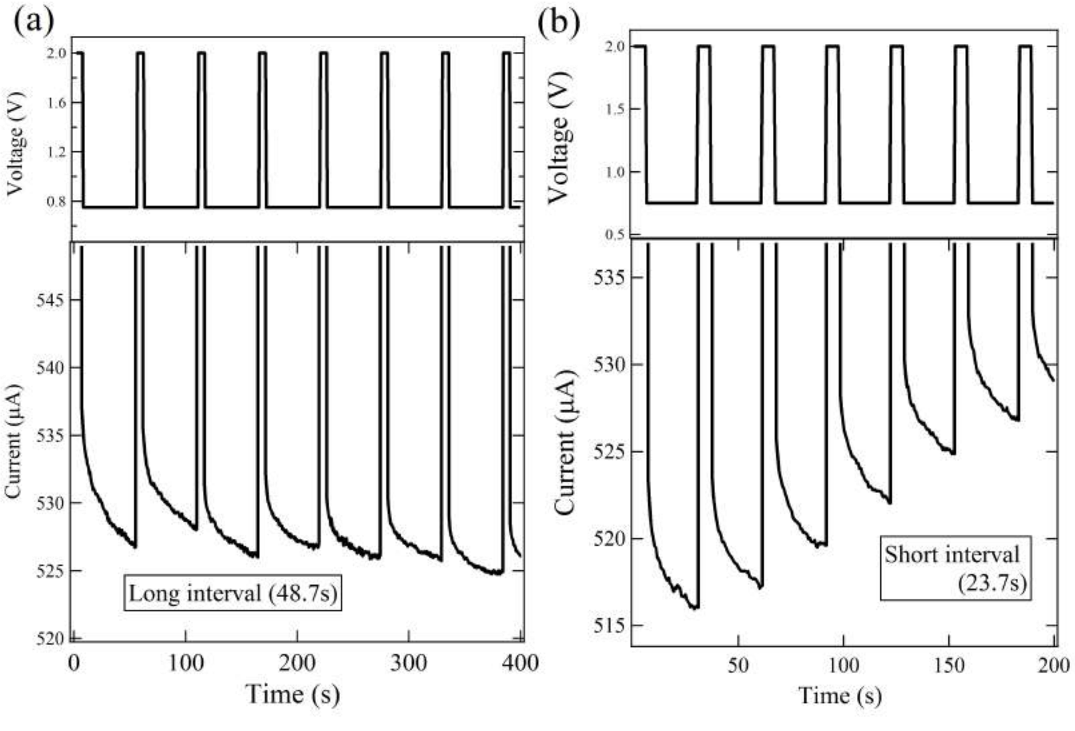

Fig. 1 (a) Short-term and (b) Long-term memorization obtained by using electrical pulse.

References:
[1] K. Kawamura *et al.*, Jpn. J. Appl. Phys., in press (2017).
[2] R. Yang *et al* Nanotechnology **24**, 384003 (2013).

P14: Presentation Title:

Surface Proton Conduction on Yttria-Stabilized Zirconia Thin Film for Nanoionic Devices Application

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Abstract:

We report structural and electrical properties of $Zr_{0.92}Y_{0.08}O_{2-\delta}$ (YSZ) thin film prepared by RF magnetron sputtering. This material is promising solid electrolyte materials with high oxygen ion conduction at high temperature region, which is used for gas sensor, solid oxide fuel cells (SOFCs) and electric double layer transistor.

The conductivity of 80 and 120 nm thicknesses in wet air was higher than that in dry air below 450 ºC as shown in Fig. 1. Activation energy in wet air of thin film with thicknesses of 80 and 120 nm were 0.56, 0.52 eV, respectively. The Arrhenius plot of 80 and 120 nm thicknesses in wet air was nonlinear at low temperature region. The conductivity and activation energy of 160 nm thickness was independent of air. Furthermore, wet-annealed YSZ thin film had hydrogen-induced level in the band gap energy region as shown in Fig. 2. These results indicate that the YSZ thin film exhibited proton conduction at the surface state of wet air in the intermediate temperature region from 300 to 450 ºC. Observation of hydrogen-induced level from XAS spectrum at the surface state of YSZ is the direct evidence of surface proton conductivity.

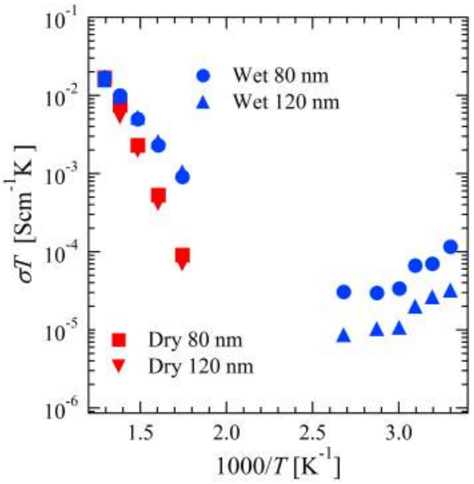

Fig. 1 Arrhenius plots of YSZ thin film with thickness of 80 and 120 nm.

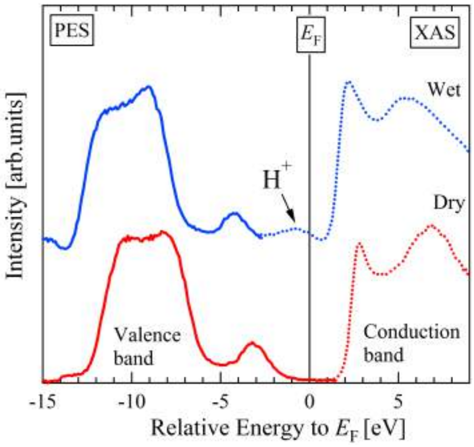

Fig. 2 Valence bands and Conduction bands obtained from PES and XAS spectra, respectively.

P15: Presentation Title:

Electrical Property of $Nd_{0.6}Sr_{0.4}FeO_3$ Thin film Deposited by RF Magnetron Sputtering Method

Authors:

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Abstract:

$La_{1-x}Sr_xFeO_3$ (LSFO) thin film is expected for cathode electrode material for solid oxide fuel cells (SOFCs). In the research of electrochemistry, LSFO thin film is well known as electron-oxygen ion mixed conductor. Although the LSFO is promising material for activation at the interface reaction between electrolyte and electrode, the chemical stability has not been proved thus far. It has reported that the chemical stability of $Nd_{0.6}Sr_{0.4}FeO_3$ (NSFO) is higher than that of LSFO. However, it has not been reported about the conductivity of NSFO thin film. Therefore, we have revealed about the conductivity of NSFO thin film deposited on Al_2O_3 (0006) substrate.

We have prepared NSFO thin film with various thickness by RF magnetron sputtering method. The film thickness was changed between 42nm and 112nm. The conductivity of the thin film exhibited thermal activation type and increased with increasing film thickness as shown in Fig.1. The activation energy of the thin film was ~0.5 eV. The valence band of the thin film consists of Fe 3*d* and bonding state hybridized with O 2*p* (α peak) as shown in Fig.2. The value of the band gap corresponded to that of the activation energy. This result indicates NSFO thin film exhibits mainly electron conduction.

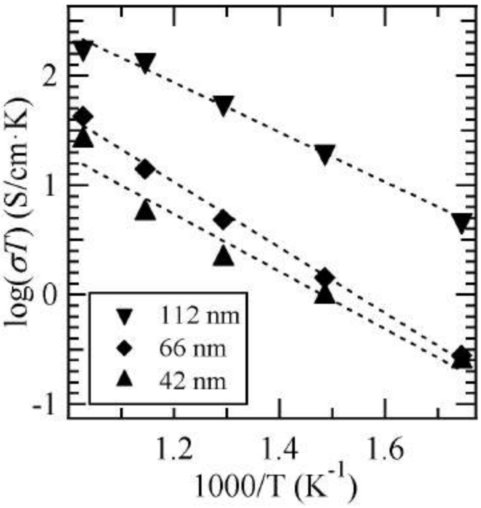

Fig. 1 Arrhenius plot of NSFO thin film with various thickness.

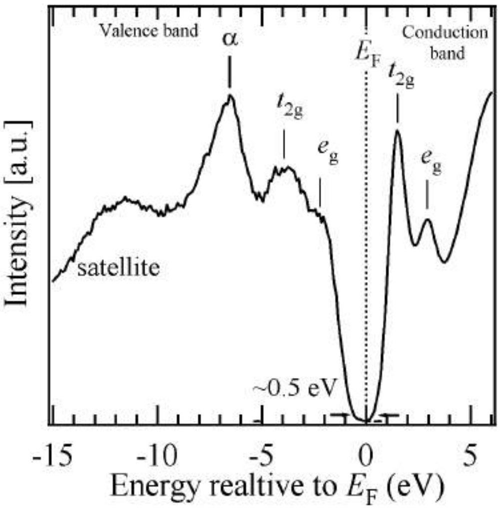

Fig. 2 Band structure of NSFO thin film.

International Symposium on
Atomic Switch
2017

Achievements of Atomic Switch Research

1. Peer-reviewed papers

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ISSN:0919-3405

2002

2. "Ionic/electronic mixed conductor tip of a scanning tunneling microscope as a metal atom source for nanostructuring"
K. Terabe, T. Nakayama, T. Hasegawa, and M. Aono
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T, Sakamoto, H. Sunamura, H. Kawaura, T. Hasegawa, T. Nakayama, and M. Aono
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2004

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