Atomic Switch for making new type of electronic devices and systems

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Further Progress by Nanotechnology

- Vacuum Technology
- Transistor
- IC
- LSI
- VLSI
- ULSI
- 4G DRAM
- Nano-electronics
  - Molecular Electronics
  - Spin-Electronics
  - Carbon-Electronics
  - Atomic Electronics
  - Quantum Computing

Year

1900
1950
2000
2050

Performance
Key point for the further progress

Miniaturization ➝ Using new functions by new materials & new structures

Molecules & Atoms smallest building blocks
Atomic Switch

Atomic movement was achieved by electrical field.
ON/OFF : 10

Atomic movement was achieved by solid electrochemical reaction.
ON/OFF : $>10^3$
OUTLINE

1. Mechanism and Characteristics
2. Application for Commercial Devices
3. New Type of Atomic Switch
Small Size and Low On-resistance

Atomic switch

Atomic movement is controlled.

Semiconductor Switch

Electronic distribution is controlled

ON resistance (Ω) vs Switch size

atomic switch

GaAs-FET
MOSFET

1nm
1μm
1mm
Operating Mechanism

Switched on

Switched off

\[ \text{Operating Mechanism} \]

\[ \text{Ag}_2S \]

\[ \text{S}^2- \]

\[ \text{Ag}^+ \]

\[ \text{Ag}_2S \]

\[ \text{Ag}^+ \]

\[ \text{Ag} \]

\[ \text{Pt} \]

\[ \text{Ag}^+ \]

\[ \text{e}^- \]

\[ \text{Ag}^+ \]

\[ \text{e}^- \]

\[ \text{Ag}^+ \]

\[ \text{e}^- \]

\[ \text{Ag}^+ \]

\[ \text{e}^- \]

\[ \text{Ag} \]

\[ \text{200 \mu m} \]
Ag nanowire growth by e-beam

Ag₂S Crystal
The two electrodes are fixed in the case of atomic switch operation.
Controlled growth and shrinkage

Growth and Shrinkage speed of Ag

\[ \frac{dN}{dt} = A \cdot \exp \left( \frac{E - D \cdot It}{kT} \right) \]

-1.5 V
-2.0 V
-2.5 V
-3.0 V
+1.5 V
+2.0 V
+2.5 V
+3.0 V

Tunneling current (nA)

Rate of change in length of Ag protrusion (nm/sec.)

growth
shrink

\[ \text{Ag} \rightarrow \text{Ag}_2\delta\text{S} \]

\[ \text{Ag}^+ \text{Ag} \]

\[ \text{Ag}^+ \rightarrow \text{Ag} \]

\[ \text{growth} \]

\[ \text{shrink} \]

\[ D_g \cdot It \]

\[ D_s \cdot It \]
Switching time vs. switching voltage

Switching characteristics depend on the materials.

Atomic switch using $\text{Ag}_{2+\delta} \text{S}$

Atomic switch using $\text{Cu}_{2-\delta} \text{S}$

- $: 1 \text{M} \Omega \text{ to } 12.9 \text{ k} \Omega$
- $: 100 \text{ k} \Omega \text{ to } 12.9 \text{ k} \Omega$

Two types of atomic switch

‘with gap’ and ‘without gap’

Initial type of Atomic switch

Gapless atomic switch (NanoBridge™)

Cross-section of NanoBridge
Switching Mechanism of gapless atomic switch

Operating Model

Applying Voltage

Cation formation and migration

Super-saturation @ Pt electrode

Metal deposition parallel to electrode

Growth toward Cu electrode

Switch ON

Metal Bridge Formation
OUTLINE

1. Mechanism and Characteristics

2. Application for Commercial Devices

3. New Type of Atomic Switch
1k-bit nonvolatile memory

Apply to Programmable Devices

Switch size reduces to 1/30, On-resistance reduces to 1/40.

Nowadays Switch

Area = 120F²
On-resistance = 2kΩ

Atomic Switch

Area = 4F²
On-resistance = 50Ω

F: minimum feature size

New device “Programmable CBIC” is proposed.

Programmable CBIC

*It enables many functions by a single chip*

- Larger number of fine-grain logic cells
- Size reduction due to the small switches

Chip size: 1/10th, or 10 times larger application
Number of programs increases vastly.

Conventional FPGA
FPGA: Field Programmable Gate Array

Programmable CBIC
CBIC: Cell Based Integrated Circuit
4x4 crossbar circuit


1.8V 0.18μm CMOS logic

Atomic switch

Insulating film

Au/Pt/Ti

Cu₂S

Cu

CMOS

4 X 4 crossbar switch

INPUT

Program 1

Program 2

OUTPUT1

OUTPUT2

OUTLINE

1. Mechanism and Characteristics

2. Application for Commercial Devices

3. New Type of Atomic Switch
   1) Atomic Switch Array using AAO Template
   2) Three terminal Atomic Switch
   3) Photon-assisted Atomic Switch
**Atomic switch array using AAO**

**Ag$_2$S/Ag nanorod and its switching property**

(a) Electrochemical plating → Electrochemical sulfurization → Removing template

- Self-made porous-alumina template (~10nm pore)
- Ag nanowire array
- Ag/Ag$_2$S nanowire array

(b) 

\[ V_{\text{in}}(V) \]

\[ I_{\text{out}}(mA) \]

"On" and "Off" states

d: 20 nm

3-terminal Atomic Switch

For more controllability, large current, etc.

3-terminal Atomic Switch

For more controllability, large current, etc.
All functions enabled by a single chip using Atomic Switch

Ubiquitous Network

Cell phones
Digital TV
Robot

Sensor

GPS

Video decoder

Communication

High Performance Programmable Device

MP3 decoder

Health care

45V

Car

Video decoder
1. Mechanism and Characteristics
   1) Atomic Switch with 1 nm gap
   2) Gapless Atomic Switch (Nano Bridge™)

2. Application for Commercial Devices
   1) Nonvolatile Memory
   2) Programmable Logic Device

3. New Type of Atomic Switch
   1) Atomic Switch Array using AAO Template
   2) Three terminal Atomic Switch
   3) Photon-assisted Atomic Switch