Development of Technology for Increasing Reliability of Logic Circuit Components

Broadening applications of spintronics logic integrated circuits

June 12: Session 7-4
Spintronics Primitive Gate with High Error Correction Efficiency
$6(P_{\text{error}})^2$ for Logic-in Memory Architecture

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NEC Corporation
Tohoku University
Growing power consumption of electronic equipment after growth of cloud computing and smartphones

Tight power supply after the Great East Japan Earthquake

Equipment should be powered off while not in use, but …

→ The startup process is time-consuming

→ Equipment is kept powered on during standby in order to maintain data

Concern about increase in standby power consumption in line with increase in equipment

Hope is placed on non-volatile logic integrated circuits based on spintronics technologies
Examples of Standby Power Consumption of Electronic Equipment

- **Desktop computer**
  
  Approx. 2.4 W in sleep mode
  
  Approx. 37 W in e-mail editing process

- **Television**
  
  Approx. 0.1 W in standby mode
  
  Approx. 18 W at maximum if quick start is enabled

In the office and at home, many different appliances consume power on standby.
Spintronics Logic Integrated Circuits with Non-Volatile Features

- Non-volatile: Data retained without power supply
- Spintronics (spin + electronics):
  Technology capitalizing on the spin of electrons (a characteristic of magnets) and negative electric charge
  → Applied to logic integrated circuits as data storage devices
  ( = Non-volatile spintronics logic integrated circuits)
- Achieving massive cuts in power consumption and performance improvement without limits on rewrite cycles

Characteristic of electrons

- Negative electric charge
- Spin of fine magnet

Conventional electronics used the electric charge alone
In many electronic appliances, integrated circuits remain powered on even in standby mode.

- Unplugging is necessary to save power.
- Power-saving electronic equipment with no need to unplug can be created.

Integrated circuits currently remain powered on when they are idle for as long as the device is in operation.

- A technology of powering off integrated circuits in operation while they are not being used.
- Optimal power-saving electronic equipment can be created.

- Ultra-low power consumption computers that immediately start up and are ready to use.
- LCD televisions without standby power consumption despite their quick startup.

**Concept of Future Application in Electronic Equipment**

Toward creating information equipment without standby power consumption and that can immediately be used.
Problems with Conventional Spintronics Logic Integrated Circuits

Problem of reliability unique to non-volatile circuits:

Low-probability occurrence of errors in failing to correctly store computation result data

(Causes: cosmic rays, high- or low-temperature heat, voltage or current fluctuations in the writing process, etc.)

Application of conventional reliability improvement method

Past designs cannot be reused → Higher design costs

Resulting chip will be larger in size → Higher manufacturing costs

Barriers to enlarging applications

*The chip size may be 25% larger if it has a cyclic circuit or 200% larger with a non-cyclic circuit.
Achievements of the Study

1. A number of spin devices that temporarily store computation results are mounted on a circuit component of a spintronics logic integrated circuit for multiplexing purposes.
   → Multiplexed spin devices serve to correct errors to achieve high reliability in the circuit.

2. The circuit component embedded with spin devices supports automatic placement and routing technology for programmed design of transistors.
   → This paves the way for designing non-volatile circuits by conventional methods without knowledge about the spin.

World’s first chip is prototyped and its operation is verified

1. The technology developed in this study in principle has an error rate of 0% (or 1 ppm or less).
2. The diagram on the left portrays the results of the test aimed at verifying the theory.
3. Since the data gained from the test agree with the theoretical data, the theory stated in 1 has been confirmed.
Spin devices (domain wall devices) are **serially connected for multiplexing**. Two spin devices are added (multiplexed) to two other spin devices to correct errors and **improve reliability**.

Spin devices are **stacked** over transistor devices. Multiplexed devices are **serially connected**.

The serial connection results in **no increase in writing current or time**.

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Reliability is increased by multiplexing of devices with no area increase.
Feature 2: Circuit can be designed without knowledge about spin

Non-volatile logic circuits can be designed by the conventional design method.
Summary and Future Outlook

- World’s first verified technology to increase reliability of non-volatile logic circuits that allows reuse of design assets
- Spin devices (domain wall devices) are multiplexed to improve reliability without increase in area
- Technology supports existing circuit design tools, including automatic placement and routing
- Chosen in FY2009 as a subject under the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program) operated by the Cabinet Office. NEC participated in this program.
- Research and development efforts target early commercialization of spintronics logic integrated circuits.

Part of the achievements from research activities on energy-saving spintronics logic integrated circuits under the Cabinet Office’s FIRST Program
Empowered by Innovation

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The free layer fine magnets are a group that tends to face in the same direction.
- The free layer is fixed at both ends with pin layers (powerful magnets) in opposite directions. 
  ➔ This forms a domain wall, or an area where the direction of fine magnets sharply changes.
- Spin torque, or interaction between electrons, moves domain walls. Depending on their positions, a data value of 0 or 1 is stored.
- CoNi, a material that turns the fine magnets in the vertical direction, is used. 
  ➔ The writing current can be reduced.

Features:
1) Low writing current of 0.2 mA or less
2) High writing speed at 5 ns or less
Conduction electrons are also fine magnets. Their interaction with fine magnets in the free layer unifies the magnets’ directions. This action is called spin torque.

- Domain walls move in the same direction as the electron flow.
- Devices can be downsized using spin torque, as an action of individual electrons.
Writing a data value of “0”:
The writing current displaces the domain wall to change the magnetic field generated.

MTJ for readout

MTJ = Magnetic Tunnel Junction
Reading a data value of “0”:
The resistance value of the MTJ that reacts to the magnetic field generated is read.

MTJ for readout

- Read pin layer
- Insulation tunnel barrier
- Read free layer

Resistance: Low
Tunnel current: High

MTJ = Magnetic Tunnel Junction
Writing a data value of “1”:
The writing current displaces the domain wall to change the magnetic field generated.

MTJ for readout

Read pin layer
Insulation tunnel barrier
Read free layer

Domain wall

Free layer
Pin layer

Domain wall displacement
Writing current

MTJ = Magnetic Tunnel Junction
Reading a data value of “1”:
The resistance value of the MTJ that reacts to the magnetic field generated is read.

MTJ for readout

- Read pin layer
- Insulation tunnel barrier
- Read free layer

Resistance: High
Tunnel current: Low

Domain wall
Magnetic field generated

Free layer
Pin layer

MTJ = Magnetic Tunnel Junction

Reference: Principle of Behaviors of Vertical Domain Wall Devices (4)
Vertical domain wall device with three terminals:

- Current routes for reading and writing are different. This facilitates writing control. (Writing can be controlled with the current direction alone.)
  → Easier writing control leads to increased speed.
- The writing current route has no resistance, to pave the way for serial connection.
  → This helps reduce the device size.

Reference: Vertical Domain Wall Device with Three Terminals