Spin-Motive Force 
as a New Energy Conversion Mechanism

“Power Spintronics”

Sadamichi Maekawa

Advanced Science Research Center (ASRC),
Japan Atomic Energy Agency (JAEA).

References:
* S. Maekawa (ed.) “Concepts in Spin Electronics” (Oxford University Press, 2006),
* S. Maekawa et al. (eds.) “Spin Current” (Oxford University Press, 2012).
TOKAI is a Science Complex of Japan with J-PARC, Neutron facility, Muon facility and so on,
JAEA’s Activities

FUKUSHIMA

Environmental safety
Plant restoration

New Institute
Cs-137 in Fukushima

Nuclear Fuel Cycles

1. FBR Cycle Technology
2. Geological Disposal Technology of HLW

Support of LWR cycle industry
HTGR & Hydrogen production

3. Fusion research & development

4. Quantum beam technology

Activity to secure safe nuclear power and peaceful use
Decommissioning & disposal of low level waste

Safety research
Nuclear nonproliferation

Cooperation with academic and industries, international collaboration, human resource development

Universal scientific technology

Basic nuclear power engineering research, state-of-the-art basic research (ASRC)
Earthquake at 14:20 on March 11, 2011

JAEA Guest House
JRR-2
LINAC-3

- The floor level sagged 4 cm downward in the tunnel. Because accelerator cavities should be aligned within ±1 mm to each other along the beam line for the operation, they have been leveled and realigned where necessary.
- Restoration work on the cooling water system and power supply is going smoothly.

Realigned accelerator cavities of DTL and SDTL were tested for watertightness.
Highway around the Mito area

16:30 on March 11

17:00 on March 17
**Clean-up Technologies**

**Clean-up of Farmland**
- Plow
- Topsoil removal, Hardening
- Turf stripping

**Clean-up of Roads and Pavement**
- High pressure water, Road clearer
- Surface stripping, Blasting, Ultra high pressure water

**Clean-up of Trees and Forest**
- Weeding
- Removal of leaf mold
- Clipping, Water horsing

**Clean-up of Housings**
- Wiping off with cloth
- Removal of the sediment in a drainspout

**Volume Reduction of Waste**
- Chipping – pruning and sticks
- Incineration

**Temporary storage for wastes**
- Shielding, Gas discharge,
- Tank for checking of radioactivity concentration of seeping water
Aircraft Radiation Monitoring

- Count rates are obtained by NaI(Tl) detector installed in a helicopter.
- Altitude above the ground: about 300 m (150 – 450 m).
- After fly-over, aerial count rates are converted to estimate the ground level dose rates and surface contamination level.
This Workshop was originally planned to be held on March 14-17, 2011 and was postponed by the Earthquake.
By Prof. T. Ziman (ILL, Grenoble):

“Experiences of a Visitor during the Earthquake”,

In Quest for the future (News Letter of ASRC) Vol. 19, No.1
(December 2011 Issue).

Dr. Lev Vidmar was with us in Tokai on March 11, 2011.
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Electron:

Spin (magnetism): $\pm \hbar/2$

Charge (electricity): $e$

Spin and charge of electron are used on an equal footing → Spintronics

(usual electronics ← charge of electron)
Magnetic domain structure in Fe:


c.f., P. Weiss: J. Phys. 6, 661 (1907),
H. Barkhausen: Phys. Z. 20, 401 (1919),
F. Bloch: Z. Phys. 74, 295 (1932),

A century ago!!
**First Spintronics:**

Bubble domain memory

\[ R \approx 1 \, \mu m \]

**1970’s**

From Micro to Nano!

**Fig. 3.117** Depending on the nature of the remanent state (*top row*) bubble states of lower or higher bubble density develop in a perpendicular field \( H_b \) beyond the stability limit \( H_{s0} \) of the band domains (*bottom row*).

How to observe a 100 nm domain → TMR junction, spin-transfer device,...
Tunnel Magnetoresistance (TMR): Current depends on Spin (spin current)!!

**Diagram:**
- Metal A: Upward Co, Metal B: Downward Ni
- Parallel and Anti-parallel configurations

**Graph:**
- Ni-NiO-Co Tunneling
- Magnetic field $H$ (Oe)
- $\Delta R$ (%) vs. $H$
- Data at $T = 4.2$ K, $V = 0$

**References:**
Tunnel magnetoresistance (TMR)

Parallel alignment

Antiparallel alignment
Giant Magnetoresistance (GMR) in magnetic multilayers

*Spin dependent transport is also realized in magnetic multilayers!!*

ferromagnetic

antiferromagnetic

The discovery of GMR opened the door of nano-electronics!!

Better read-out heads for pocket-size devices

The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Albert Fert

Peter Grünberg

1/2 of the prize

France

1/2 of the prize

Germany

Université Paris-Sud;
Unité Mixte de Physique
CNRS/THALES
Orsay, France

b. 1938

Forschungszentrum Jülich
Jülich, Germany

b. 1939

The next work of this type was carried out by Maekawa and Gr Schönert (1989). They investigated structures of the type Ni/ NiO/FM, where FM stands for Fe, Co or Ni. The magnetoresistance they found was of
Spintronics

First generation:
Discovery of GMR (1988), TMR (1975-),
“Electric current control by magnetization”

Second generation:
Spin-transfer torque (1996),
Spin Seebeck effect (2008),
Spin Motive-force (2007) (Power spintronics)…..
“Electric voltage generation by magnetisation”
“Device size of 10-100nm”
…….
Spin current

Electric current

Spin current &

Spin current

Electric current

Spin current
Current and Spin current:

Current (charge)

\[ J_e = J_{\uparrow} + J_{\downarrow} \]

Spin current

\[ J_s = J_{\uparrow} - J_{\downarrow} \]
Domain wall motion

\[ \theta = 2 \cot^{-1} e^{-(z-z_0)/w} \]

Current \( \rightarrow \) torque on DW

\[ \frac{\partial \theta}{\partial t} \neq 0, \quad \frac{\partial \phi}{\partial t} = 0 \]

*Massless motion!*

*Spin transfer torque*
Current-driven domain wall motion (head-to-head domain wall)

$1.2 \times 10^8 \text{ A/cm}^2, 5 \mu\text{s}$

DW moves opposite to current direction.

(courtesy of Prof. T. Ono (Kyoto University))
Ferromagnetic metals

Magnetization

Electric current

interaction

angular momentum conservation

spin-transfer torque

energy conservation

spin-motive force
Electromagnetism:

Faraday’s law:

\[ \mathcal{E} = -\frac{d\Phi}{dt} \]  

Maxwell Equation:  

(1831)  

(1865)

Dirac equation:  

Q.M. + Special Relativity

Electron should have  

“spin.”  

(1928)

“spin current + electromagnetism = spintronics”
Faraday's Law:

\[ \mathcal{E} \equiv \frac{1}{-e} \oint_c \mathbf{f}_e \cdot d\mathbf{r} = -\oint_c \frac{\partial \mathbf{A}}{\partial t} \cdot d\mathbf{r} = -\frac{d\Phi}{dt} \]

Case i:

- induced electromotive force

\[ \mathbf{f}_e = (-e)\mathbf{E} = (-e) \left[ -\nabla \varphi - \frac{\partial \mathbf{A}}{\partial t} \right] \]

- force acting on electron

conservative
non-conservative
Spin-Motive Force

- Spin-motive force

\[ E_{s}^{\pm} \equiv \frac{1}{-e} \oint_{C} f_{s}^{\pm} \cdot dr \]

\[ \{ \quad \begin{array}{c}
\uparrow : \text{up spin} \\
\downarrow : \text{down spin}
\end{array} \]

- Force acting on “spin”

\[ f_{s}^{\pm} = -\nabla \varphi_{s}^{\pm} - \frac{\hbar}{2} \frac{\partial A_{s}^{\pm}}{\partial t} \]

- Spin-vector potential

\[ A_{s}^{\pm} \equiv 2i \left< \psi_{k}^{\pm} \mid \nabla_{r} \psi_{k}^{\pm} \right> \]

- Conversion from smf to emf (in ferromagnets)

\[ E_{e} = pE_{s}^{+} \quad \text{\textbf{p: polarization}} \]

\( (\text{Generalized Faraday’s Law}) \)
Case ii: spin Berry phase

\[ \mathcal{E} = -\frac{d\Phi}{dt} \]  \hspace{1cm} (1831)  \hspace{1cm} (Faraday’s Law)

\[ \mathcal{E} = \frac{\hbar}{(-e)} \frac{d\gamma}{dt} \]  \hspace{1cm} (2007)  \hspace{1cm} (Generalized Faraday’s Law)

\[ \gamma = \gamma_e + \gamma_s \]

\[ \begin{cases} 
\gamma_e = \frac{(-e)}{\hbar} \Phi \\
\gamma_s = -\frac{\Omega}{2} 
\end{cases} \]
Faraday’s law of induction:
(after The Feynman Lectures on Physics (1964))

Modern electrical technology began with Faraday’s discoveries!!
Electromotive force due to *static* magnetic field

- Domain wall moves from left (high energy) to right (low energy)
- Magnetic energy is converted to electrical energy

\[ \varepsilon = \frac{gP}{e} \mu_B H \]

(S.E. Barnes and S. Maekawa, PRL 98, 246601 (2007))

- Domain wall precesses while moving through the wire
- Emf = time derivative of Spin Berry phase \( \gamma \)

\[ \varepsilon = -\frac{\hbar}{(-e)} \frac{d\gamma}{dt} \]

Static magnetic field can induce *emf* via spin-charge energy exchange

\( \neq \) *Inverse process* of current induced magnetization reversal (CIMR)

(courtesy of M. Tanaka and P. N. Hai (U. of Tokyo))
Electromotive force and spinmotive force

- Faraday’s law -

**Change of charge Berry’s phase**
induces electrical field.

\[
\mathcal{E}_{\text{charge}} = -\frac{\hbar}{(-e)} \frac{d}{dt} \gamma_{\text{charge}}
\]

Courtesy of K. Tanabe (Kyoto Univ.)
-Faraday’s law-

**Change of charge Berry’s phase**
induces electrical field.

$$\mathcal{E}_{\text{charge}} = -\frac{\hbar}{(-e)} \frac{d}{dt} \gamma_{\text{charge}}$$

By analogy to EMF, **change of the spin Berry’s phase**
induces electrical field, which is \textbf{SMF}

$$\mathcal{E}_{\text{spin}} = -\frac{\hbar}{(-e)} \frac{d}{dt} \gamma_{\text{spin}}$$


*Courtesy of K. Tanabe (Kyoto Univ.)*
Two important points for SMF:

1. non-uniform spin structure
2. its dynamics
Experiments of spinmotive force


Yang et al., PRL 102, 067201 (2009); Hayashi et al., (PRL)

Tanabe, Chiba et al., (Nature Coomun.)

Yamane et al., PRL 107, 236602 (2011).
**SMF Case (1):**  
emf due to domain wall motion

$$\mathcal{E}_s = \frac{\hbar}{e} \frac{d\phi}{dt} = \frac{g\mu_B}{e} H$$

**Fig. 4.** Measured wall velocity (open symbols) and wall-induced voltage (solid symbols) versus drive-field. Solid line is fit with slope $10 \text{ nV/Oe}$

**Electromotive force due to domain wall motion in a NiFe nanowire.**

Yang et al., PRL 102, 067201 (2009)
(Real Time observation)

- Permalloy nanowires: e-beam lithography
- Dimension: 100-600 nm wide, 10-20 nm thick

Sign of the voltage: Left moving vs. right moving DW

- Sign of the voltage reverses when the motion direction is altered

*Real Time observation!*

Continuous generation of SMF by FMR    (Saitoh Group)

(Y. Yamane et al.:PRL107, 236602 (2011))
(intensity and frequency of microwave are 200mW and 9.43GHz respectively)
microwave power dependence of the spinmotive force

(Y. Yamane et al.: PRL 107, 236602 (2011))

Continuous generation of SMF!!
**Magnetic Disc** $\rightarrow$ **Magnetic vortex**


**Resonant motion of vortex core**

![Image showing magnetic discs and vortex cores with measurement data]
Voltage

Vortex core

Gyrating motion
When an AC current is injected to the electrode using the Signal generator, an AC field is induced by the ac current and is applied to the magnetic vortex. Then an core resonance motion is excited and the SMF voltage is induced in the disc. The voltage between the pillars is amplified and detected by the distal oscilloscope.

The shape and the order of amplitude are consistent.
The experimental result is well reproduced by the simulated one.
Deformation from sine wave shows locality of SMF near the core.

Permalloy disc (Thickness: 40nm) 

Core reversal by pulse magnetic field 

Induced elecyclic field 

Magnetization 

Bx 

Time 

Magnetic field: 

\[ B_x = B \sin 2\pi \omega t \] 

\[ B = 10 \text{Oe} \] 

\[ \omega = 200 \text{MHz} \] 

**Generalized Faraday’s Law!!**
## Energy conversion by spin motive-force:

<table>
<thead>
<tr>
<th>DC Field</th>
<th>AC Field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC Voltage</strong></td>
<td><strong>AC Voltage</strong></td>
</tr>
</tbody>
</table>


[Diagram](#)
Summary:

“Second Generation in Spintronics”

1) Angular momentum conservation,

   Spin Transfer Torque: electric control of magnetization

2) Energy conservation,

   Generalized Faraday’s Law: Spin Motive Force
   Conversion of magnetic energy to electric energy.

New Paradigm:

Spin current + Electromagnetism!!

“The modern electric industry started with the Faraday’s law”.