Future R&D strategies of magnetic NEMS/MEMS sensors

Lab. for NanoBioEngineering & SpinTronics

김철기
신물질 전공, DGIST
http://www.nbest.org

목차

Ⅰ 연구 개요
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Ⅲ 새로운 연구 방향
Ⅳ PHR 센서 특징
Ⅴ MEMS PHR 센서 응용
Ⅵ 마무리

황제(黃帝)

전설에 따르면 기원전 2500년경 중국의 황제(黃帝)는 도술로 안개를 피우는 치우와 싸울 때 자철석을 사용해 안개 속에서 길을 찾았다고 한다.
Navigation in nature

Earth’s magnetic field to navigate their way home over long distance!!

Pigeons ‘sense magnetic field’

Bee has magnetic resonance

Magnetic sense in Fish: Tuna

Magnetosomes

Diagnostics

I. 연구 개요

- 바이오 자성 물리
- MEMS 센서 연구

Therapy
Diagnostics: "Bio-magnetics"

- **Lab-on-a-chip**
- **Physical, thermal imaging**
- **Single cell analysis**
- **Molecular Diagnostics**

### DNA Hybridization
1-3 kcal/mole

### Antigen & Antibody binding
240 pN

### Avidin & biotin binding
150 pN

### DNA & protein interaction
1 kcal/mole

### Target molecule

### Probe molecule

#### Development
- DNA hybridization (1-3 kcal/mole)
- Antigen & Antibody binding (240 pN)
- Avidin & biotin binding (150 pN)
- DNA & protein interaction (1 kcal/mole)

#### Cells on chips

- **Developed nano/Micro-technologies**
- **Lab-on-a-chip**
- **Cells on chip**
- **Magnetic based new nano/micro-technologies**

#### Homogeneity

#### Heterogeneity

- **Single cell analysis**
- **Celltronics** (cell + tronics)

- **Digital magnetophoresis**
Tasks for magnetic "Lab-on-a-chip"

Superparamagnetic label

Barcodes

Magnetic microfluidics

Magnetic sensor

~ fM, multiplexing, high throughput
II.

MEMS 센서 상업화
- MEMS 자기센서 (Hall & MR)
- 상업화 제품 (E-compass)

Solid 자기센서/모듈 세계시장 규모

GLOBAL MARKET FOR VARIOUS TYPES OF ROTATIONAL MOTION SENSORS, THROUGH 2015 (IN MILLIONS)

<table>
<thead>
<tr>
<th>Types of Rotational Motion Sensors</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>CAGR % 2005-2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable reluctance sensors</td>
<td>468</td>
<td>411</td>
<td>411</td>
<td>405</td>
<td>396</td>
<td>11.1</td>
</tr>
<tr>
<td>Graded core sensors</td>
<td>383</td>
<td>431</td>
<td>425</td>
<td>403</td>
<td>390</td>
<td>11.1</td>
</tr>
<tr>
<td>Hall effect sensors</td>
<td>725</td>
<td>735</td>
<td>766</td>
<td>793</td>
<td>820</td>
<td>33.6</td>
</tr>
<tr>
<td>MEMS sensors</td>
<td>178</td>
<td>200</td>
<td>300</td>
<td>255</td>
<td>210</td>
<td>11.1</td>
</tr>
<tr>
<td>AMR sensors</td>
<td>113</td>
<td>170</td>
<td>270</td>
<td>185</td>
<td>120</td>
<td>30.9</td>
</tr>
<tr>
<td>GMR sensors</td>
<td>117</td>
<td>200</td>
<td>200</td>
<td>323</td>
<td>423</td>
<td>11.1</td>
</tr>
<tr>
<td>Other miscellaneous types</td>
<td>110</td>
<td>115</td>
<td>160</td>
<td>160</td>
<td>200</td>
<td>11.1</td>
</tr>
<tr>
<td>Total</td>
<td>2,071</td>
<td>2,440</td>
<td>3,050</td>
<td>3,010</td>
<td>2,500</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Source: BCC Inc.

자동차용 자기센서
Magnetoresistive effects

Voltage in magnetic materials

\[ \tilde{V} = R_1 \tilde{I} + (R_n - R_0) \tilde{m}(\tilde{I} \cdot \tilde{m}) + (R_p - R_{sp}) \tilde{I}(\tilde{m}_1 \cdot \tilde{m}_2) + R_{sh}(\tilde{H} \times \tilde{I}) \]

- AMR/PHR: Spin-Orbit coupling
- GMR/TMR: Spin-Scattering
- Hall effect: \( R_H = 1/\pi e \)

E-compass 응용

지구 자기장

차세대 compass
- 정밀
- 가격

Low power
Low Cost
Compass 센서의 가격 절감 요소

새로운 센서의 לצורך

- Size 감소
- 제조비 절감
- 단가 절감

- 오도 센서 병행 사용
- 단가 절감

ASIC
- 전압변환 전성
- AMP Gain
- A/DC

- 전압 변환 장치
- 각도 변환 장치
- Offset 최적화

Compass 센서의 가격 절감 요소

- 단가 절감
- 제조 비용 절감

- 오도 센서 병행 사용
- 단가 절감

- 전압 변환 장치
- 각도 변환 장치
- Offset 최적화

최적화 위치

통작 삐통

Magnetic Field (mT)

-15 -10 -5 0 5 10 15
-4.00 -4.06 -4.12 -4.18 -4.24 -4.30 -4.36
상업화된 E-compass

**Asahi Kasei ➔ Semiconductor Hall 센서**
Sn doped single crystal film InSb is used as a material for the sensing element

<table>
<thead>
<tr>
<th>Company</th>
<th>Compass type</th>
<th>Specifications</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asahi KASEI</td>
<td>6-axis Electronic Compass</td>
<td>1. 3-axis magnetometer and 3-axis accelerometer</td>
<td></td>
</tr>
<tr>
<td>Microdevices</td>
<td></td>
<td>2. Measurement range: ±1200µT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. 14/16 bit digital output</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Resolution: 0.3 µT (14-bit)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Operation modes: single, continuous and external trigger measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6. Operating Temperature: -30°C to +85°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. Current consumption: 350µA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8. packages: 26 pin (3.0x5.0x1.0 mm)</td>
<td></td>
</tr>
</tbody>
</table>

Yamaha ➔ GMR type

특허: Magnetic field-sensitive sensor device with a plurality of GMR sensor elements which have predetermined directions of magnetization US 5945825 A

<table>
<thead>
<tr>
<th>Company</th>
<th>Types</th>
<th>Specifications</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yamaha</td>
<td>YAS525R-biaxial geomagnetic sensor</td>
<td>1. 2-axis magnetometer</td>
<td>GPS system and mobile phone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Measurement range: ±300µT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Resolution: &lt;0.6 µT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Operating Temperature: -20°C to +85°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. power supply: 2.5V~3.3V</td>
<td></td>
</tr>
</tbody>
</table>
**Alps Electric**

<table>
<thead>
<tr>
<th>Company</th>
<th>Types</th>
<th>Specifications</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alps Electric</td>
<td>HSCD Series 3-axis Geomagnetic Sensor</td>
<td>**</td>
<td>- Electronic compasses (smartphones, digital still cameras, etc.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Motion control (game controllers, head-mounted displays, etc.)</td>
</tr>
</tbody>
</table>

**Specifications**

- **Product name**: HSCD Series
- **Dimensions**: (W x L x H) 50mm x 70mm x 5mm
- **Magnetic field measurement range**: ±0.6mT
- **Output resolution**: 0.5μT / LSB
- **Operating temperature**: -20°C to +85°C
- **Supply voltage (analog)**: 7.4V type
- **Supply voltage (digital)**: 1.8V type
- **Average current consumption (when active)**: Max. 200 μA
- **Average current consumption (when on standby)**: Max. 5 μA

**NIKON AF-S DX NIKKOR 18-200MM LENS → GMR Sensor**

We can also see the GMR (Giant Magnetoresistor) unit — the slivery piece held on by two screws at the left of the image below. The GMR is the position sensor Nikon and many third-party lenses use.

In the spirit of ‘don’t do what I did, do what I say’, I’ll tell you don’t ever touch that with a finger.

If you do the lens no longer works and the unit has to be replaced by Nikon and Aaron will give you that look he gives when you’ve done something really stupid.
**Tokina AT-X 16-28mm f/2.8 Pro FX Lens**

AT-X 16-28 F2.8 PRO FX - Tokina | Digital Eyes - Visionary ...
www.tokinalens.com › Tokina › AT-X PRO FX

... of full frame (FX) lenses designed for professional digital SLR cameras like the ...
The 16-28 f/2.8 uses a newly developed silent DC motor that allows the lens to ...

The DC motor coupled with a new GMR magnetic AF sensor work together to ...
Focus Clutch Mechanism allows the photographer to switch between AF and ...

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**AICHI MI 3D COMPASS (JAPAN)**

The AMI302 is a small, three-axis MI sensor IC module that integrates three orthogonal positioned Magneto-Impedance sensors with their controller IC in a single small package to sense three-dimensional magnetic field strengths. ➔ GMI

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**HONEY WELL SENSORS (USA)**

The HMR3500 TruePoint™ compass module is a 3-axis digital compass solution with a customizable coordinate system for mounting in any desired orientation. Three Anisotropic Magneto-Resistive sensors and three MEMs accelerometers are combined to provide compass heading as well as pitch and roll angles. ➔ AMR
The TCM family of sensor modules combines PNI's patented magneto-inductive sensors with a 3-axis MEMS accelerometer in a single temperature- and noise-stabilized design that's inherently free of offset drift. Broad range of navigation and tracking applications.

LAAN LABS (USA)
The 3D compass (or half-sphere compass/nautical compass) is just like what you find on a beautiful yacht or airplane. Unlike other compasses you can view it in any orientation.

MK3Mag – MIKROCOPTER Compass Module (GERMANY)
3D Compass Module kit with ACC-Sensor (SMD-preassembled). This is a 3-axis magnetic field sensor.

GMR ANGLE SENSOR, ROBERT BOSCH, GERMANY
새로운 연구방향

- portable, flexible 소자
- 유연기판 자기 센서 연구

새로운 연구방향? Electronics ??

Wearable device

Substrate, electrode, circuitry elements
- Display[1,2], transistor[3,4]
- Radio-frequency identification (RFID)[7]
- Bio-chemical sensors[8-10]

Light, cost effective, wearable, implantable devices

Flexible magnetic sensors

- Magnetoelectronics: Fabricated by sputtering

GMR on polyester substrate

- Stretchable GMR on PDMS

2.5% tensile strain

4.5% tensile strain


Nano lett. 11 (2011) 2522
G. Schmidt, Germany

Flexible magnetic sensors

- Printing & Sputtering

Printable GMR

Co/Cu GMR powder

MTJ on organic substrate

G. Schmidt, Germany

A. Fert, Orsay, France
Flexible magnetic sensors

- Printing & Sputtering
  
  **Printable GMR**
  
  Cu/Cu GMR powder

  ![Image of GMR powder and sensor](image.png)

  
  G. Schmidt, Germany

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**IV. Planar Hall effect sensors**

- Why PHR? (PHR 특성)
- 본 연구팀 연구결과
- Flexible 센서
• Lorentz force

\[ \mathbf{F} = -q(\mathbf{v} \times \mathbf{B}) \]

In steady state this force is balanced by the force set up by the Hall voltage, so that there is no net force on the carriers in the \( y \) direction

\[ \mathbf{F}_y = -qE_y - q(\mathbf{v} \times \mathbf{B}) = 0 \]

\[ \Rightarrow E_y = v_x B_z \]

\[ I = -qnv_y t W \Rightarrow v_x = -I / qnt \]

\[ E_y = -\frac{IB}{nqtW} = \frac{R_H IB}{tW}, \quad R_H = \frac{1}{nq} \]

\[ E_y = E_y W = \frac{R_H IB}{t} \]
AMR and PHR 특성

Angular dependence of AMR and PHR

Field dependence of AMR and PHR

\[ R_{\alpha} = R_1 + (R_2 - R_1) \cos \theta \]

\[ R_{\beta} = (R_{\beta} - R_1) \sin \theta \cos \theta \]
Noise characteristics

- **Noise Sources**
  - Barkhausen noise: due to the domain movement
    - Dominant factor in flux-gate magnetometer
  - Thermal noise (Johnson noise)

- **Noise characteristics of F/AF bilayers**
  - Nearly no Barkhausen noise
    - Single domain structure
    - Domain Rotation
  - Small thermal noise of PHR
    - \[ V_{N_{rms}} = \sqrt{4k_B T R_{DC} N_f}, \quad R_{AMR} \approx 5 \Omega, \quad R_{PHR} \approx 0.1 \Omega \]
    - Reduce the thermal draft by 2 orders of magnitude

---

S/N ratio of Magnetic Sensors


<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>( H_k - H_{ex} ) (Oe)</th>
<th>( H_{bas} ) (Oe)</th>
<th>( \Delta R ) (mΩ)</th>
<th>( S ) (mΩ/Oe)</th>
<th>( B_{max} ) (nT)</th>
<th>( S/N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMR</td>
<td>10</td>
<td>2</td>
<td>50</td>
<td>8</td>
<td>25</td>
<td>280</td>
</tr>
<tr>
<td>Planar Hall effect</td>
<td>10</td>
<td>15</td>
<td>1450</td>
<td>32</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>SV</td>
<td>10</td>
<td>87</td>
<td>442</td>
<td>54</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>GMR</td>
<td>5</td>
<td>13</td>
<td>382</td>
<td>93</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Hall</td>
<td>0.3</td>
<td>0.03-4</td>
<td>3-300</td>
<td>200</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>MTJ</td>
<td>1.0</td>
<td>10</td>
<td>114</td>
<td>200</td>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>

L. Ejsing, et. al. 60 15 100 15 1450

CNU sensor 14 6 80 25 2800

\[ V_{N_{rms}} = \sqrt{4k_B T R_{DC} N_f}, \quad \leftarrow R_{GMR} \approx 3 \Omega, \quad R_{PHR} \approx 0.1 \Omega \]
**PHR Sensitivity**

\[ \frac{\Delta R}{\Delta H} = \frac{R_H - R_S}{2(H_{ex} + H_{k})} \]

- NiFe(30 nm)/NiO
- \( \Delta R/\Delta H \approx 0.003 \text{ ohm/Oe} \)

Sensitivity can be tuned by changing the \( H_{ex} \).

---

**Sensor development In our Lab**

1. Sensor development in our Lab
3. IEEE TRANSACTIONS ON MAGNETICS, VOL. 45, NO. 10, OCTOBER 2009
4. IEEE TRANSACTIONS ON MAGNETICS, VOL. 45, NO. 6, JUNE 2009
8. JOURNAL OF APPLIED PHYSICS 107, 09E715 2010
Layer structure \[1\]: Reducing shunt current

**Requirement:**
- Reducing shunt current
- Keeping thermal stability

\[ \text{IrMn: } 210 \mu \Omega \cdot \text{cm} \]
\[ \text{NiFe: } 20 \mu \Omega \cdot \text{cm} \]
\[ \text{Cu: } 1.7 \mu \Omega \cdot \text{cm} \]

\[ I_{\text{active}} = 30\% \text{ (spin-valve)} \]
\[ I_{\text{active}} = 60\% \text{ (trilayers: Cu1.2 Å)} \]

\[ S : 6.0 \mu \text{V/} \text{Oe} \Rightarrow 12 \mu \text{V/} \text{Oe} \]
\[ \times 13 \text{ times} \]

10-2010-0054238 특허출원, T. Hung et al, JAP 107, 09E715 (2010)

Layer structure \[1\]: exchange coupling field

**Multilayer Structures**

- **Bilayer**
  - Anisotropy: uniaxial
  - Exchange bias role:
  \[ H_a = \frac{t}{t_{\text{ex}}} \]
  \[ H_L - H_H \]
  \[ \text{oscillation} \]
  - Planar Hall effect: 20 mV/T

- **Spin-valve**
  - Anisotropy: uniaxial
  - Exchange bias role:
  \[ H_a = \text{exp}\left(-\frac{t}{t_L}\right) \]
  - Planar Hall effect: 60 mV/T

- **Trilayer**
  - Anisotropy: uniaxial
  - Exchange bias role:
  \[ H_a = \text{exp}\left(-\frac{t}{t_L}\right) \]
  - Planar Hall effect: 120 mV/T

**Planar Hall effect**

- Planar Hall effect: 20 mV/T
- Planar Hall effect: 60 mV/T
- Planar Hall effect: 120 mV/T

**Heisenberg Interaction**
\[ \sigma = \frac{2JS}{\mu_0} \text{ and } S \]
\[ \sigma : \text{coupling energy density} \]
\[ J : \text{exchange constant (} -2 \times 10^{-8} \text{ erg}) \]
\[ a : \text{lattice spacing (} -2 \times 10^{-8} \text{ cm}) \]
### Geometrical structure [2]: Self-balanced bridge type

- Solid State Comm. 151, 1248 (2011)
- JAP 113, 063903 (2013)

Vector Ohm’s law

\[
\hat{E}(\theta, \alpha) = \hat{\rho}(\theta) \hat{J}(\alpha)
\]

\[
R_i = \frac{r}{\alpha} \left( (2\rho_i + \Delta \rho) \frac{\pi}{4} + \frac{(-1)^{i+1}}{2} \Delta \rho \sin 2\theta \right)
\]

with \( \Delta \rho = \rho_i - \rho_j \)

### Feature of resistance variation

\[
R = \frac{1}{2} \sum_{i=1}^{4} \int_{0}^{\pi/2} \rho_i (\alpha, \theta) d\alpha = \frac{\pi r}{2\alpha} \sum_{i=1}^{4} \left( 2\rho_i + \Delta \rho \right) \frac{\pi}{4} \left( 1 - \frac{1}{2} \Delta \rho \sin 2\theta \right)
\]

\[
V_{\text{out}} = \frac{1}{2} (R_1 - R_3 + R_2 - R_4) \cdot \frac{I}{2}
= ((V_1 + V_4) - (V_2 + V_3))/2
\]

\[
V_{\text{out}} (H, T) = \frac{\pi r}{2\alpha} I \Delta \rho (T) \sin 2\theta (H)
\]

\[
V_{\text{PHE}} = \frac{I}{2} (R_1 - R_3 + R_2 - R_4)/2
\]

- Constant terms: cancel
- \( V \) for 4 arms: additive
IV. MEMS PHR 센서 응용예
- \(\mu\)-magnetometry (solid, liquid 시료)
- Biochip sensor (1D, 2D 플랫폼; 바이오 시료)
- 그외 MEMS 센서 (E-compass, 전류센서)

\[ \text{SQUID: bulk} \]

Bistable phases
metal center-ligand bond

LS: \( S = 0 \); Dia.
HS: \( S = 2 \); Para.

Fe\(^{2+}\) (d\(^6\))

Size distribution: 250 ± 40 nm
Transition: 310 - 330 K
Low susceptibility: \(4.2 \times 10^{-4}\) (SI)
\( \mu \)-magnetometry (1): phase change detection

Resolution \( \sim 10^{-13} \) emu
Temperature: 80 – 500 K
Performed at L2C Montpellier

Magnetometry measurement
Sensor size: 300 \( \mu \)m

Photo reflectivity measurement
\( \lambda = 550 \pm 40 \) nm

1. Q.H. Tran et al., Angew Chem Int Ed. 52, 1185 (2013)
3. L2C in collaboration with LCC Toulouse and Korea

\( \mu \)-drop generation

\( L=50 \) \( \mu \)m
\( W=40 \) \( \mu \)m, \( t=10 \) \( \mu \)m

\( L=100 \) \( \mu \)m

\( L=120 \) \( \mu \)m

Volume: \( \sim 40 \) pL

Adjusting parameter:
\( \Rightarrow \) pressure of solution

Monitoring droplet

Droplet length: \( L = 100 \, \mu\text{m} \)
Field: 15 Oe

M-H curve of droplet

1% (30 pL)
6.61 x 10^{-9} \, \text{emu}
Is it reasonable?

Table: Magnetometer Sensitivity (emu) Dynamic range

<table>
<thead>
<tr>
<th>Magnetometer</th>
<th>Sensitivity (emu)</th>
<th>Dynamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSM</td>
<td>10^-8</td>
<td>Wide [1,5]</td>
</tr>
<tr>
<td>AGM</td>
<td>10^-8</td>
<td>Middle [2,5]</td>
</tr>
<tr>
<td>SQUID</td>
<td>10^-8 ≤ 10^-11</td>
<td>Narrow [3,5]</td>
</tr>
</tbody>
</table>

1. www.lakeshore.com

1 emu = 10^-3 µA = 10^-3 A · m²

Dipole field

\[ m = 4 \pi H \]

\[ H = \frac{4 \pi}{3} \mu_0 \sin \theta \cos \theta + \frac{4 \pi}{3} \mu_0 \sin \theta \cos \theta \]

SQUID: \( r_{spp} \approx \mu_0 (10^{-1} \text{m}) \)

Our system: \( r_{spp} \approx 10 \mu m (10^{-5} \text{m}) \)

\( \left( V_{spp}, V_{set} \right) \approx 10 \)

Same moment resolution: \( 10^{-1} \times 10^{-2} \times 10^{-3} \)

Applications [4]: Biosensor and biochip

1D assay application (Cardiac Troponin I (cTnI))

Sensors and Actuators B 160 (2011) 747–752
## Applications [5]: Biosensor and biochip

### Performance test: biotin–streptavidin

![Image](image.png)

### Summary of MR biochip resolution

<table>
<thead>
<tr>
<th>Research group</th>
<th>Sensor type</th>
<th>Sensor size</th>
<th>Label size</th>
<th>Molecular resolution</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bielefeld Univ. Germany</td>
<td>GMR</td>
<td>180 µm (dia)</td>
<td>350 nm 860 nm</td>
<td>800 fM (protein) (2008)</td>
<td>---</td>
</tr>
<tr>
<td>Phillips Research Europe, Holland</td>
<td>GMR</td>
<td>- - -</td>
<td>300 nm 500 nm</td>
<td>0.8 pM (protein) (2008)</td>
<td>---</td>
</tr>
<tr>
<td>Univ. Minnesota, USA</td>
<td>GMR</td>
<td>80µm x 40µm</td>
<td>12 nm</td>
<td>0.3 fM (protein) (2009)</td>
<td>4 µL</td>
</tr>
<tr>
<td>Stanford Univ. USA</td>
<td>GMR</td>
<td>93µm x 3µm</td>
<td>100 nm 50 nm -3µm</td>
<td>5 fM (protein) (2010)</td>
<td>---</td>
</tr>
<tr>
<td>Chungnam Nat’l Univ. Korea</td>
<td>PHR</td>
<td>50µm x 50µm</td>
<td>100 nm</td>
<td>3 fM (protein) 2013</td>
<td>1µL</td>
</tr>
</tbody>
</table>
Prof. Shan Wang group

Research group | Sensor field sensitivity (μV/Oe.mA) | Label size (nm) | Biological limit of detection | Biological agent | Reference
--- | --- | --- | --- | --- | ---
Stanford Univ. (S. X. Wang) USA | 35.8 | 50 | 5 fM | Protein | Biosens Bioelectron. 25 (2010) 2051
CNU (C.G. Kim) Korea | ??? | 20 | ??? | ??? | ???

(a) Real-time monitoring of different concentrations of E. coli with magnetic beads using a hybrid sensor signal for the quantitative analysis of bacteria detection with the addition and removal of magnetic beads and (b) signal change in relation to the number of E. coli (Inset: SEM image of bacteria-bead conjugates).

E-coll detection

Magnetic particle

1st antibody

Cell (bacteria)

2nd antibody

Biosensors and Bioelectronics 41 (2013) 758–763
V. 마루리
- R & D 전략
- 활용 분야
미무리: 활용분야

National Key Industries
- 모바일용 3D compass, GPS, 내비게이션
- 자동차용 Position/Angle/Speed 자기센서
- Smart Grid용 전류문서
- Wearable Device

Military Use
- 수중 물체, 장비 감시기
- 고감도 목표 식별기기
- 개인 휴대용 감지기기

Academic Research
- 정밀 자기측정 장비
- 지하 지형 및 광물 탐색 연구
- 차세대 Organic substrate – inorganic device 활용

Bio-Medical Purposes
- 고성능 바이오-분자 센서 합
- 단일 생체분자 검출
- 의약품 연구, 개발