Wireless communication systems for nano/micro sensors

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Internet of things

- IoT has evolved multiple technologies including sensors, embedded systems, communication, real-time analytics or machine learning.
- For hardware concept, sensor network is one of key technologies.
Introduction

Micro/ Nano size sensors

- Smaller size of sensor can make various applications
- Various micro/nano sensor concepts have been suggested.
  - Due to its size effect, it can minimize damages or harmful effects to embedded system.
  - Human body, Bridge, etc.
- However, a supply of power and a control signal transmission are rarely even considered.
RF communication technology

RF communication

Design parameters

RF antenna theory: $\lambda = f(L)$

- Antenna size: nanometer - micrometer level
- Working frequency: THz - PHz
**RF communication technology**

- **Nano/micro size antenna**
  - **Design of nano antenna**
  - **Nano antenna fabrication and analysis**
  - **Test of interference situation for multi antenna**

- **Micro size antenna**

- **There are lots of issues to convert from EM wave to electrical signal.**
  - No electrical components or electrical measurement devices for THz-PHz region
Optical communication technology

- Optical wireless communication

- **LED (Tx) + Image sensor (Rx)**
  - Micro LED & Micro image sensor
  - SNR issues for outdoor environment
  - Even IR wave, it is hard to penetrate into human body or walls of building.
### Magnetic coupling communication

**Wireless transmission**

<table>
<thead>
<tr>
<th>Method</th>
<th>Transfer distance</th>
<th>Advantage</th>
<th>Problem</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) RF transmission (EM wave)</td>
<td>Long distance (~km)</td>
<td>Long distance</td>
<td>Selectivity of matter</td>
<td>Radio Mobile phone Satellite</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Antenna directivity</td>
<td></td>
</tr>
<tr>
<td>2) Magnetic Inductive coupling</td>
<td>Short distance (~1m)</td>
<td>High efficiency Non-selectivity of matter</td>
<td>Short distance</td>
<td>Tooth brush, etc</td>
</tr>
</tbody>
</table>

- EM wave shows serious attenuation for liquid base matters
- Magnetic inductive coupling is appropriate to nano/micro sensor, since it can work inside of body or liquid base ambience.
Development of Antenna & TFT combined system

1. Antenna issue
   - Decreasing WPT efficiency at low frequency level and small size of antenna
     - Flat spiral coil is suitable in wireless TFT system due to fabrication process and design issue
     - To apply to micro sensors, the size of antenna needs to be minimized as micro-size.

2. Thin film transistor (TFT) issue
   - Decreasing mobility of TFT at high frequency level

- Not only magnetic antenna, but also some electrical components such as switch, rectifier or amplifier require for wireless power and signal transmission.
- As one of building block for various applications, antenna and TFT combined system were suggested and studied.
As scaling down the size of antenna, the wireless transmission efficiency is decreased.

We should enhance this electromagnetic characteristics.

Improvement using magnetic core structure

- When the ferro-magnetic material is located in the center of coil pattern, the inductance value can be enhanced by inducing a higher magnetic flux in the center.
- Enhancement of magnetic flux leads to increase the inductance of coil.

\[ B = \mu_0 H + \mu_0 \chi_m H = \mu_0 (1 + \chi_m) H = \mu_r \mu_0 H \]

- \( B \): Magnetic flux density
- \( H \): Magnetic flux
- \( \mu_r \): Relative permeability of magnetic core
- \( \chi_m \): Susceptibility of magnetic core
Various core designs

Presence of Magnetic Core (MC)

Solution for size effect

Various magnetic core (MC) structures in center of the micro antenna to increase the magnetic flux density without changing the size of the antenna structure.
**Inductance according to the MC effect**

1. The inductances of all of the micro coils with various MC structures >> The inductance of The simple micro coil design without MC

2. Increasing the effective area density of Ni with ZnO NWs: Effectively increasing the inductances from ~12 nH (coil A) to ~20 nH (coilE)

3. Insulating the MCs with SiO2

\[ Q = \frac{\omega L}{R_s} \]

\[ \eta_{12} = \left( \frac{k^2 Q_1 Q'_2}{1 + k^2 Q_1 Q'_2} \right) \left( \frac{Q_2}{Q_2 + Q_L} \right) \]

\[ Q'_2 = \frac{Q_2 Q_L}{Q_2 + Q_L} \]

**Q2 factor according to the MC effect**

1. Increasing \( Q_2 \) : Improving the Wireless power transfer efficiency

2. MC structure induces highest Q factor
Characteristics according to MC effects II

Inductance according to the MC effect
1. The inductances of all of the micro coils with various MC structures >> The inductance of The simple micro coil design without MC

Inductance according to the MC effect
1. All case show the highest transferred voltage around 22.4MHz.
2. It is mainly due to the resonance frequency of TX antenna
Results & Discussion I - antenna

**Geometry Effect of Transmission Coil (Tx)**

Receiving Coil (Rx) 1000 μm / 800 μm

**Contact pad:** Al (170 nm)
**Coil:** Cr/Au (50/120 nm)
**Width:** 40 μm
**Spacing:** 10 μm

Solenoid coil #1
- Diameter: 10 cm
- Coil thickness: 0.1 mm
- 17 turn (height 2 cm)

Solenoid coil #2
- Diameter: 5 cm
- Coil thickness: 0.1 mm
- 17 turn (height 2 cm)

Solenoid coil #3
- Diameter: 1 cm
- Coil thickness: 0.1 mm
- 17 turn (height 2 cm)
**Results & Discussion I - antenna**

- **Geometry Effect of Transmission Coil (Tx)**

**Geometry effect of transmission (TX) coil for micro size magnetic induction coil**

1. Working distance depends on the diameter of Tx coil.
   - Working distance, smaller than the diameter of Tx coil, assures the high transmission efficiency of power.
2. Smaller size deviation between Tx and Rx is better, if working distance is smaller than the diameter of Tx.

Results & Discussion I - antenna

**Multi-Tx concept**

Double Coil System

Achievement by Small floating coil with the higher power efficiency
Results & Discussion II - TFT

Issues of Thin Film Transistor (TFT)

Problem
1. Considering the increase in self-resonance frequency with decreasing antenna size
2. Increase of operating frequency due to the increase of self-resonance frequency

Solution to increase the operating frequency of TFT
1. Requirement to drive the TFT at high frequency
2. An amorphous indium gallium zinc oxide TFT (α-IGZO TFT) structure, which shows higher mobility than an α-Si TFT
Characteristics of α-IGZO TFT

TFT Features and The Performance

1. \( Wc(100 \, \mu m), \, Lc(10 \, \mu m), \) and \( Ci(17.4 \, nF) \)

2. Corresponding field-effect mobility \( \mu_{FE(sat)} : 13 \, cm^2/V_s \)

3. The following on-off ratio was about \( \sim 10^7 \)

Frequency Response

1. Gradual decreases over the 10 kHz up to MHz level

2. The proper operating frequency limit of α-IGZO TFT: Around 10 ~ 100 kHz for the wireless system
**Wireless signal transmission in TFT (Antenna connection to S-D)**

**Frequency characteristics**

1. The proper operating frequency with the highest output VDS: 10 kHz in both cases
2. The coil E with much better signal transfer characteristics than coil A for the TFT connection due to the MC effect

**Transfer characteristics**

1. The coil E with much better signal transfer characteristics than coil A for the TFT connection due to the MC effect
2. Well controllable wirelessly received drain voltage by the gate voltage

Results & Discussion III - Antenna + TFT

**Wireless switching effect of TFT (Antenna connection to Gate)**

**Rectifying characteristics**
1. The output voltage difference at 20 VPP of TX antenna swing: About 3.4 mV
2. The rectified voltage through the Schottky diode and capacitor: About 0.2 V

**Electrical characteristics**
1. Well controllable wireless TFT by wireless gate voltage
2. The corresponding on-off ratio is about $10^3$
Future applications

Wireless micro-miniaturized bio sensor
Detection of bio molecules in more confined and smaller spaces and wireless transportation of the information

Micro-robot System
Micro robots to be able to perform complex work in same spot of human body while activating independently
Future applications

Wireless Neural Probe
Selective transmission and reception of the neural of electrical signal