The 14th U.S. – Korea
Forum on Nanotechnology

Wireless communication systems for nano/micro sensors

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Introduction

- **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.

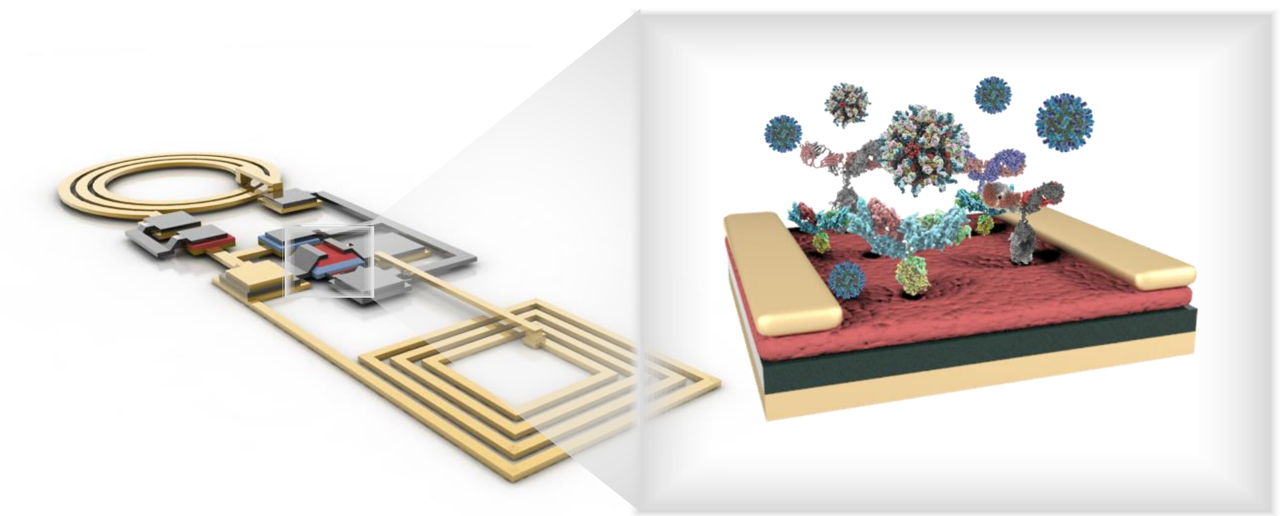
Introduction

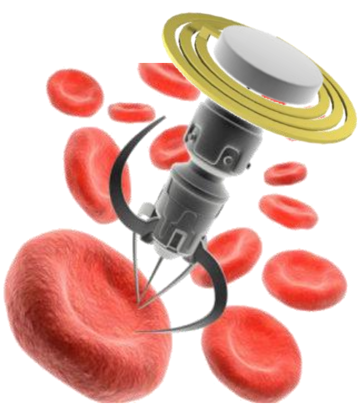
Micro/ Nano size sensors

- Smaller size of sensor can make various applications
- Various micro/nano sensor concepts have been suggested.

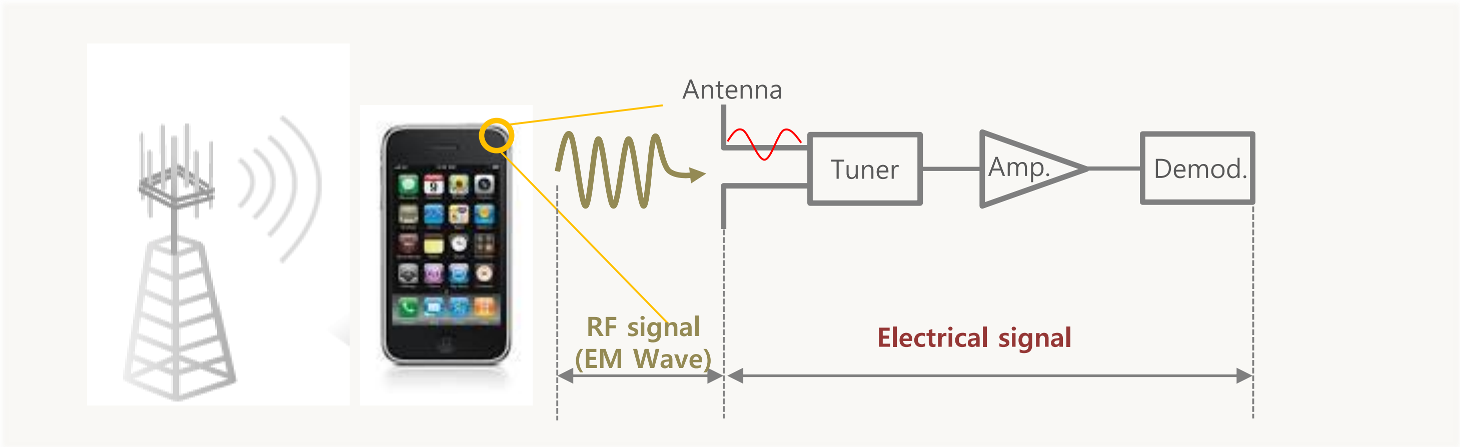
  : Due to its size effect, it can minimize damages or harmful effects to embedded system.

  : Human body, Bridge, etc.
- However, a supply of power and a control signal transmission are rarely even considered.



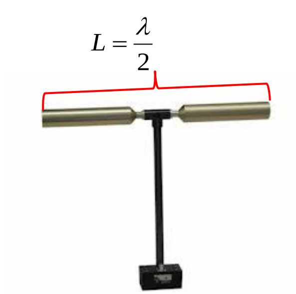


RF communication



Design parameters

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



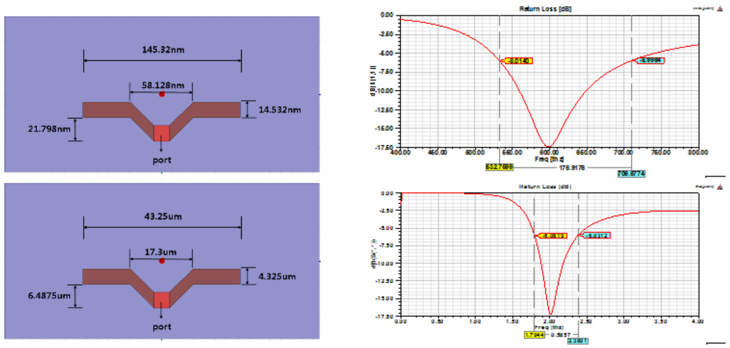
Dipole Antenna

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

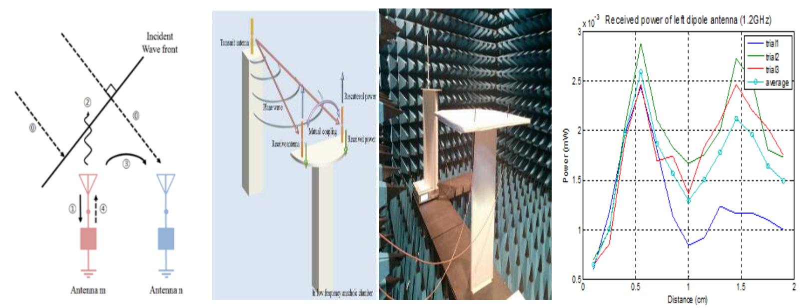
RF communication technology

Nano/micro size antenna

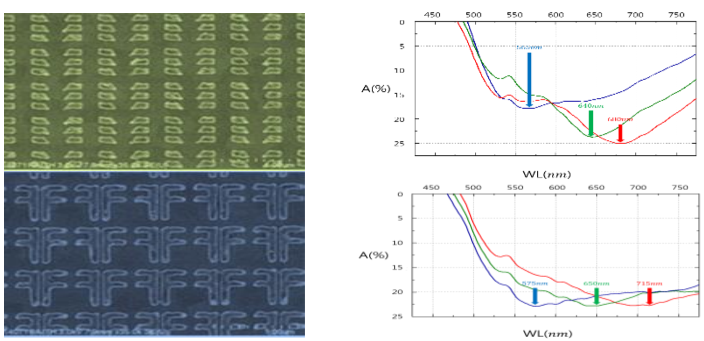
Design of nano antenna



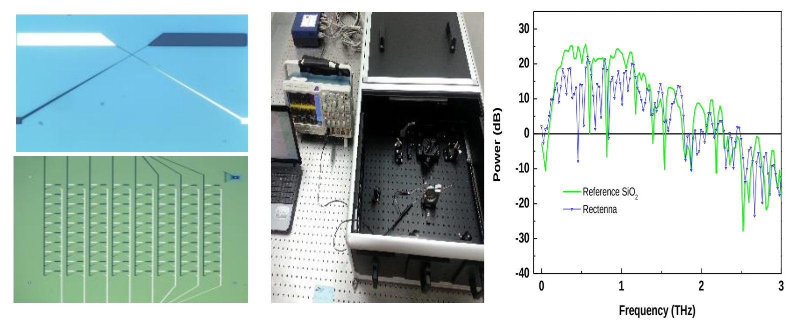
Test of interference situation for multi antenna



Nano antenna fabrication and analysis

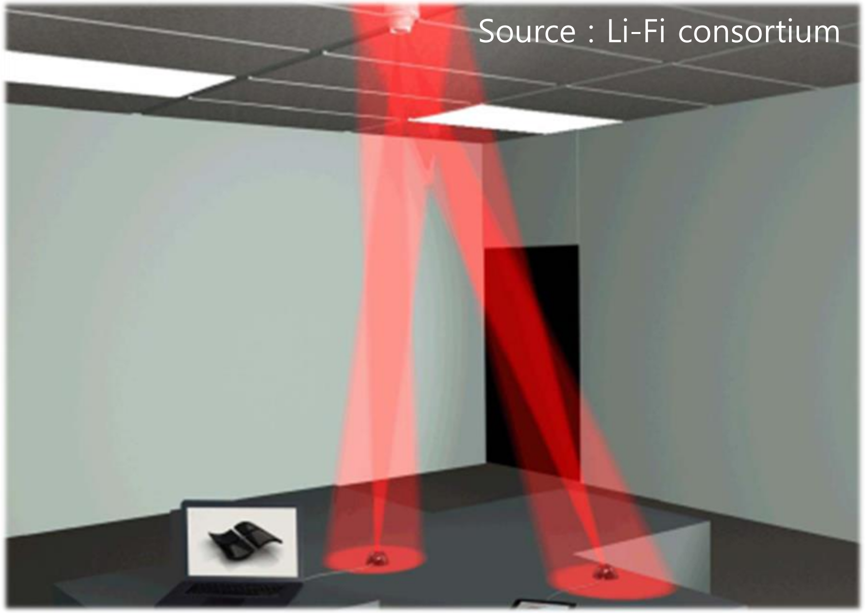


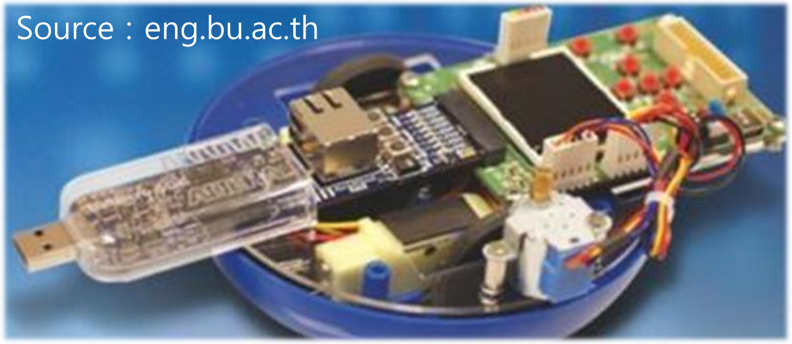
Micro size antenna



- **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 wireless communication

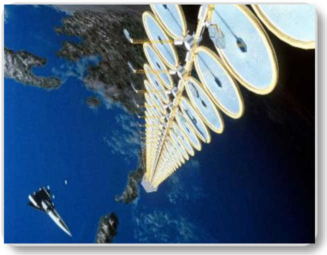




- **LED (Tx) + Image sensor (Rx)**
  - **Micro LED & Micro image sensor**
  - **SNR issues for outdoor environment**
  - **Even IR wave, it is hard to penetrate into human body or walls of building.**

Magnetic coupling communication

Wireless transmission



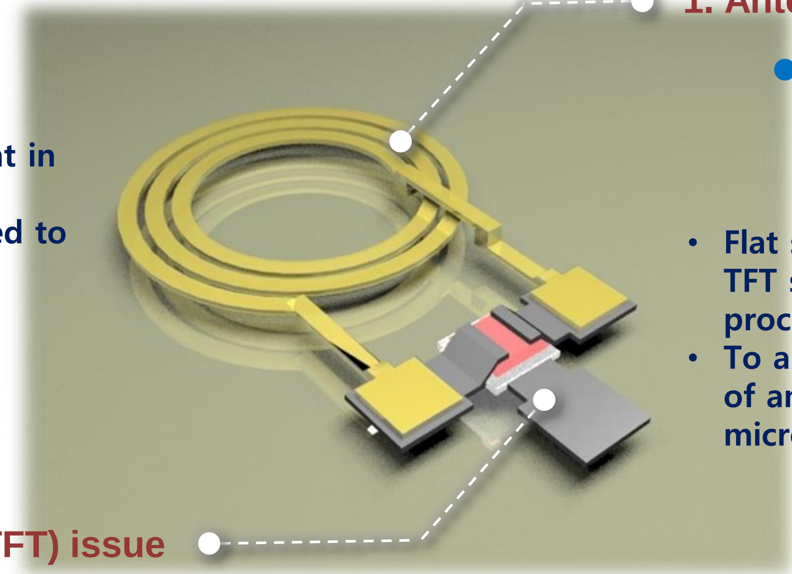
	Transfer distance	Advantage	Problem	Application
1) RF transmission (EM wave)	Long distance (~km)	Long distance	Selectivity of matter Antenna directivity	Radio Mobile phone Satellite
2) Magnetic Inductive coupling	Short distance (~1m)	High efficiency Non-selectivity of matter	Short distance	Tooth brush, etc

- 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.

Magnetic coupling communication

Development of Antenna & TFT combined system

- Transistor can be core element in electronic system .
- Transistor needs to be adopted to flexible system, so TFT is appropriate for this concept



1. Antenna issue

- **Decreasing WPT efficiency at low frequency level and small size of antenna**

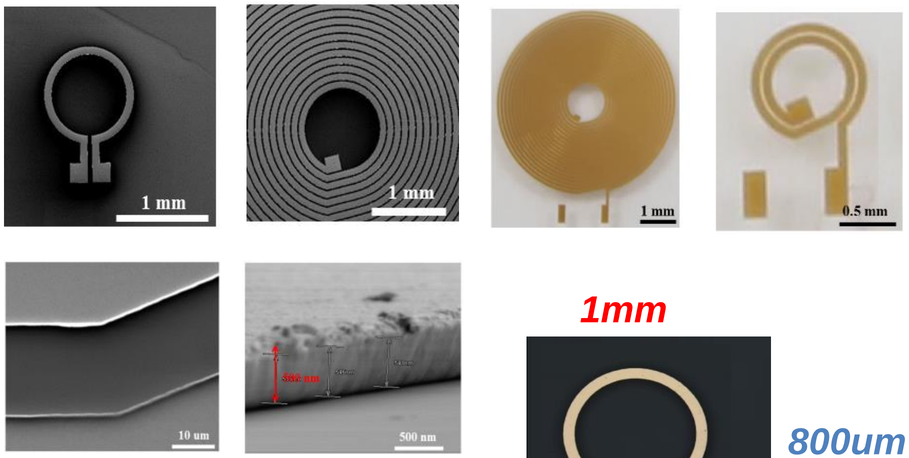
- Flat spiral coil is suitable in wireless TFT system due to fabrication process and design issue
- To apply to micro sensors. the size of antenna needs to be minimized as micro-size.

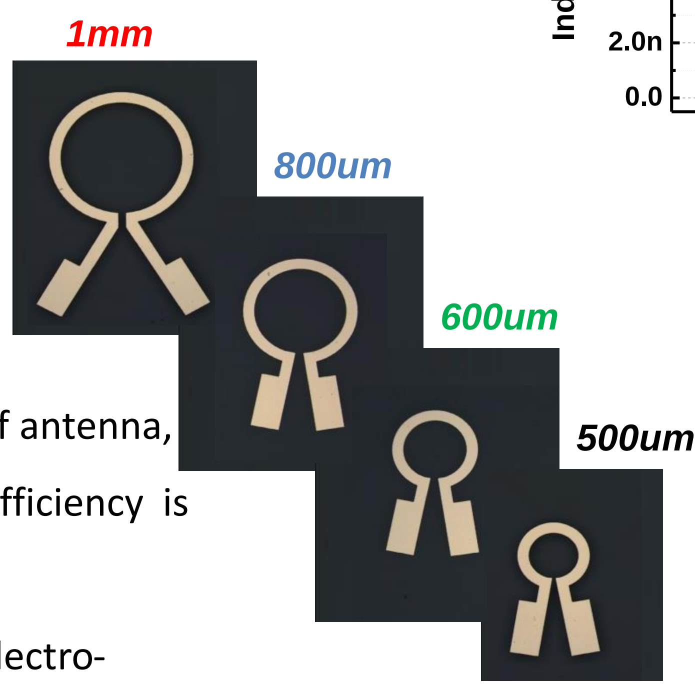
2. Thin film transistor (TFT) issue

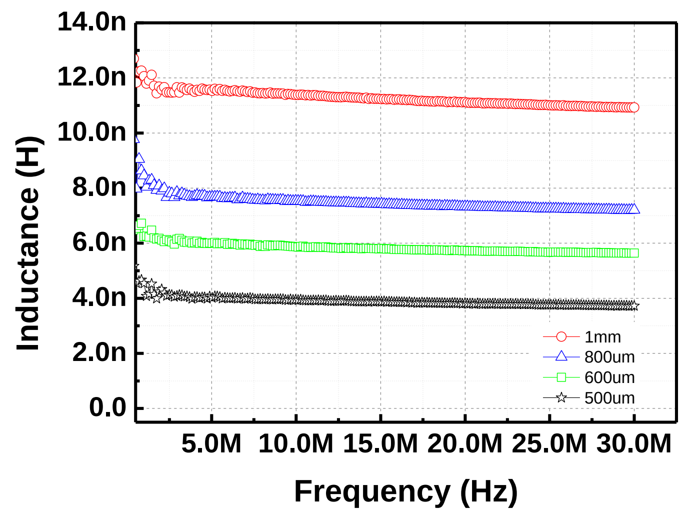
- **Decreasing mobility of TFT at high frequency level**

- 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.

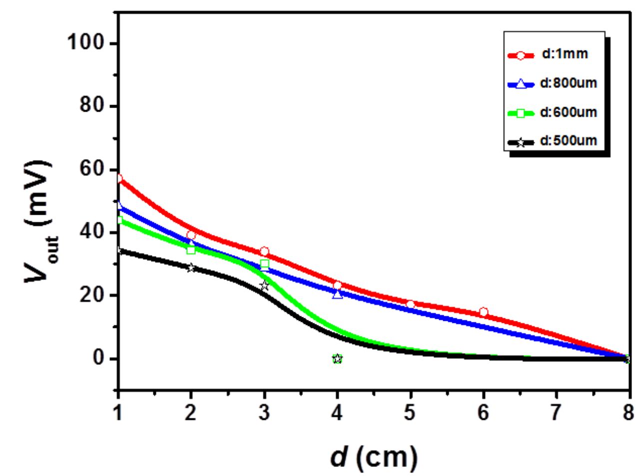
Micro magnetic antenna





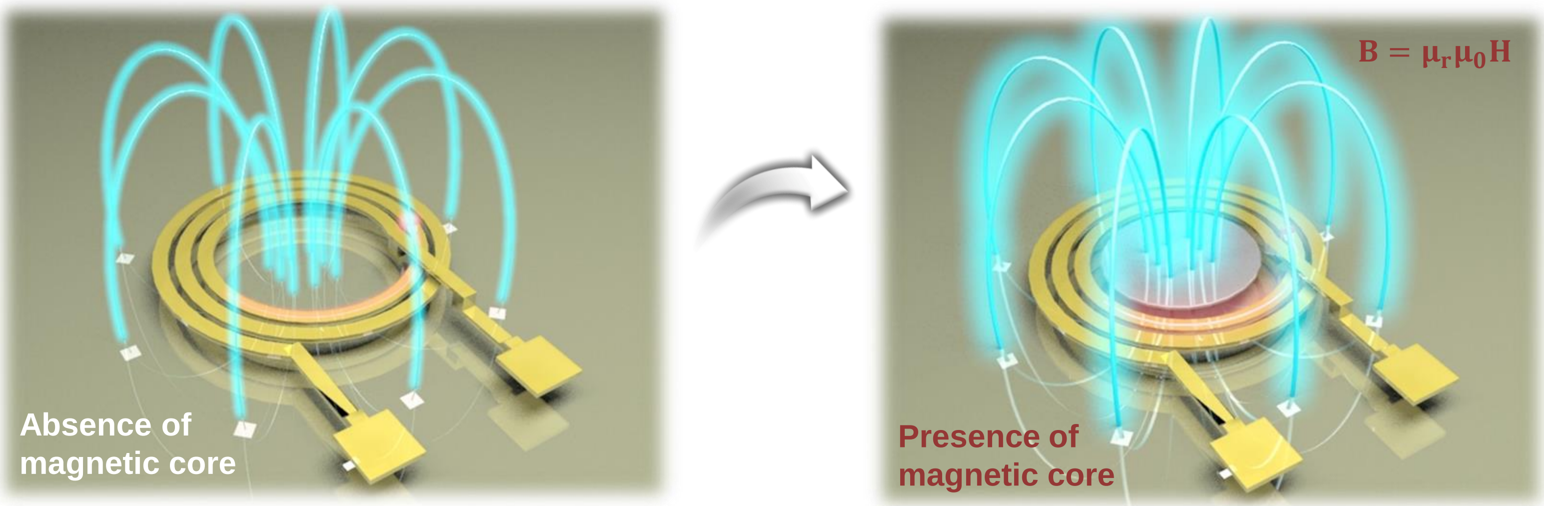


- As scaling down the size of antenna, the wireless transmission efficiency is decreased.
- We should enhance this electro-magnetic characteristics.



J. Kang, *et.al*, “Micro-size Antenna Structure with Vertical Nanowires for Wireless Power Transmission and Communication”, ***J. Nanoscience &Nanotechnology***, 14, (2014)

Improvement using magnetic core structure



$$B = \mu_0 H + \mu_0 \chi_m H = \mu_0 (1 + \chi_m) H = \mu_r \mu_0 H$$

B: Magnetic flux density
H: Magnetic flux
μ_r: Relative permeability of magnetic core
χ_m: Susceptibility of magnetic core

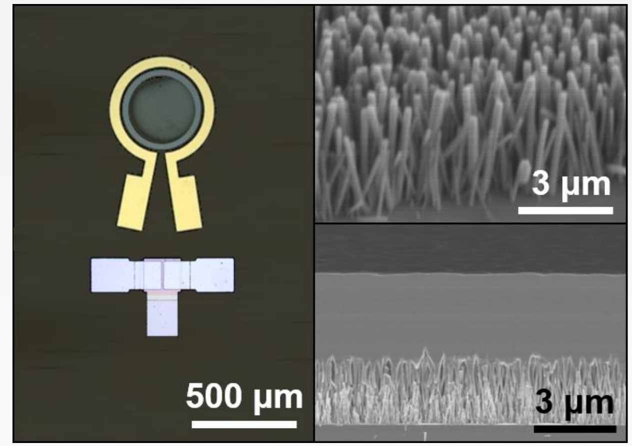
- When the ferro-magnetic material is located in the center of coil pattern, the inductance value can be enhanced by inducing a higher magnetic flux in the center.
- Enhancement of magnetic flux leads to increase the inductance of coil.

Results & Discussion I - antenna

- **Various core designs**

Coil A (without MC)

Presence of Magnetic Core (MC)

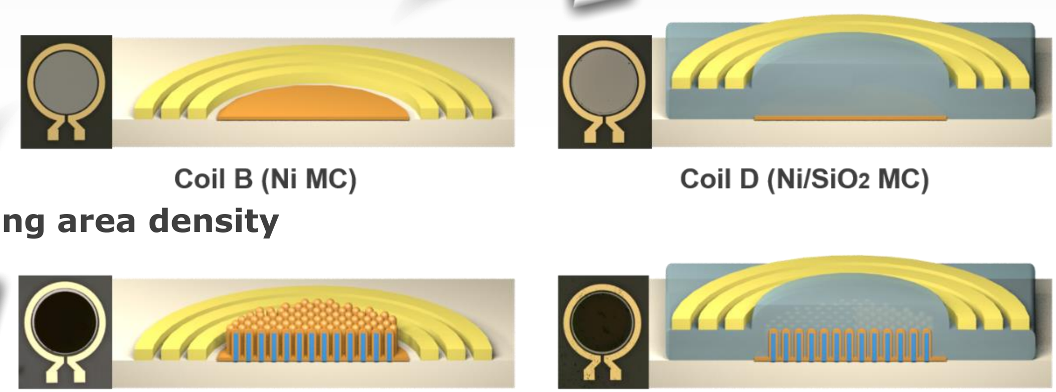


Solution for size effect

: 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.

Suppressing eddy current effect

Increasing area density



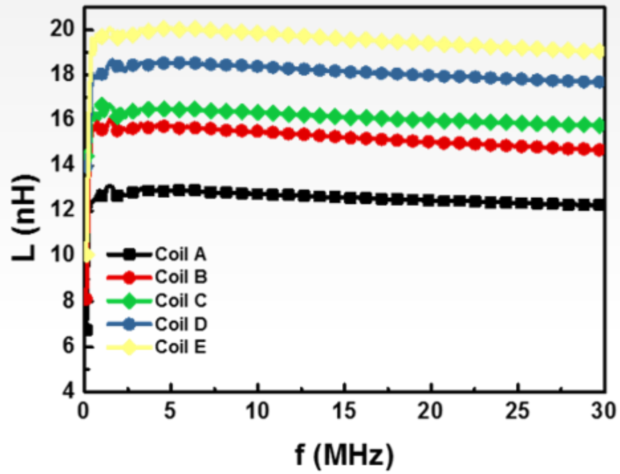
Coil B (Ni MC)

Coil D (Ni/SiO2 MC)

Coil C (ZnO NWs/Ni MC)

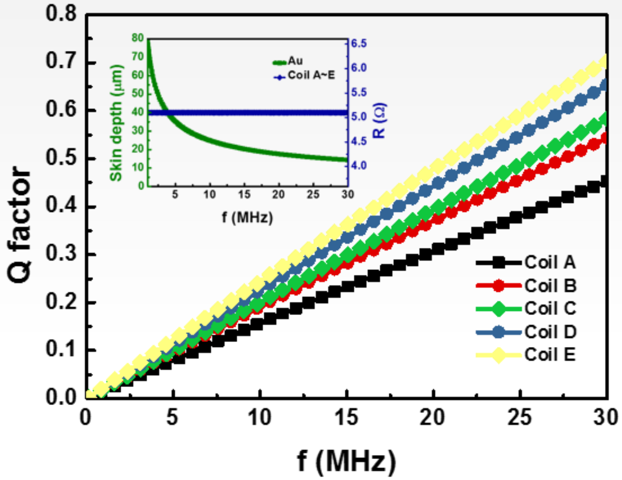
Coil E (ZnO NWs/Ni/SiO2 MC)

Characteristics according to MC effects I



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 SiO_2

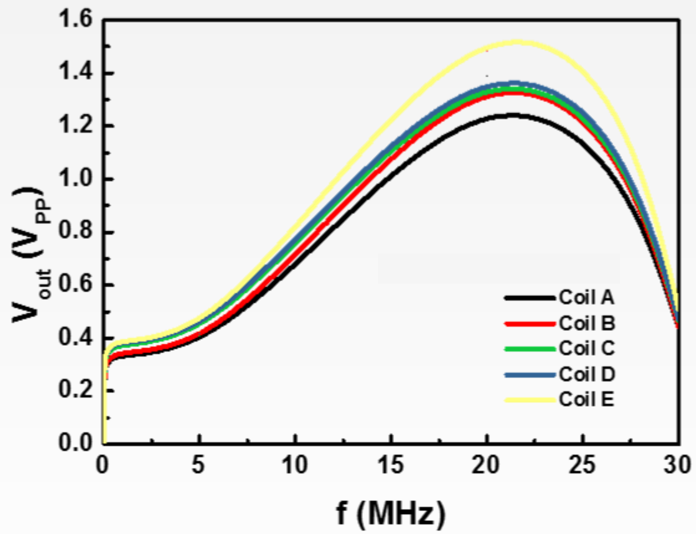


$$Q = \frac{\omega L}{R_s} \qquad \eta_{12} = \left(\frac{k^2 Q_1 Q_2'}{1 + k^2 Q_1 Q_2'}\right)\left(\frac{Q_2}{Q_2 + Q_L}\right) \qquad Q_2' = \frac{Q_2 Q_L}{Q_2 + Q_L}$$

Q_2 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

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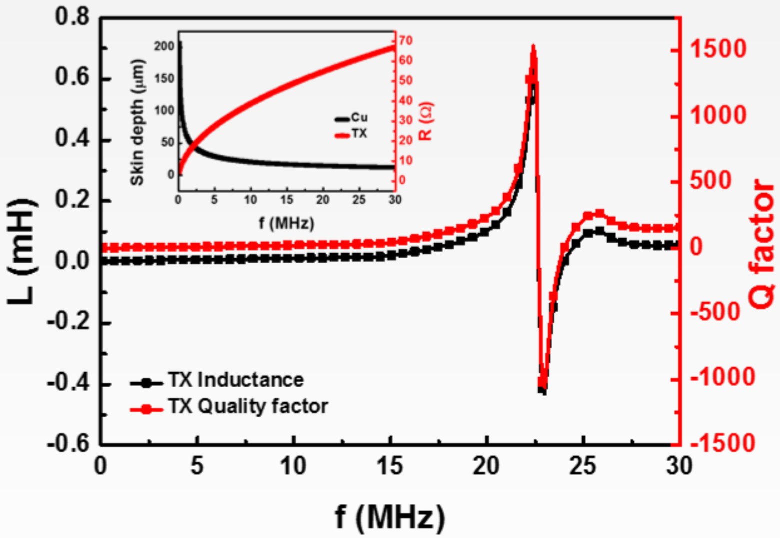


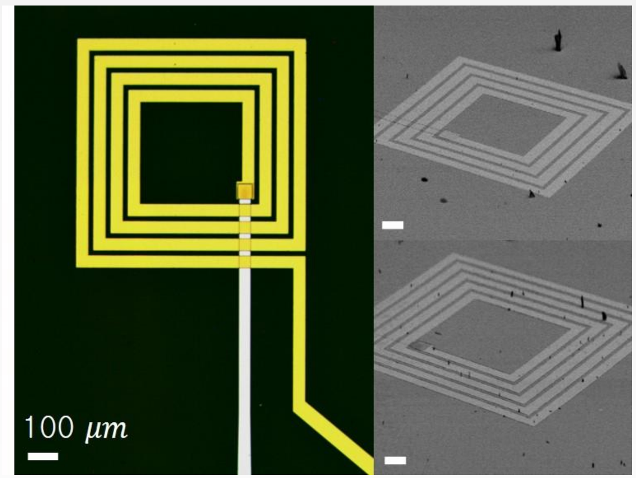
Inductance according to the MC effect

1. All case show the highest transferred voltage around 22.4MHz.

2. It is mainly due to the resonance frequency of TX antenna

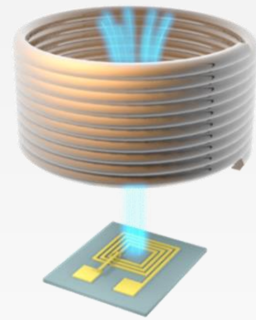
Results & Discussion I - antenna

Geometry Effect of Transmission Coil (Tx)

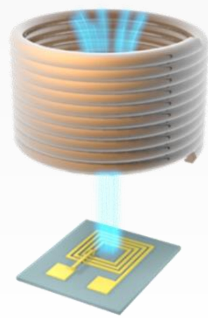


Receiving Coil (Rx) 1000 μm / 800 μm

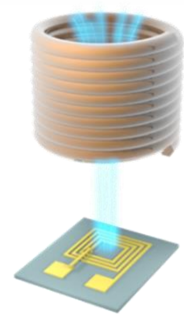
Contac pad : Al (170 nm)
Coil: Cr/Au (50/120 nm)
Width: 40 μm
Spacing: 10 μm



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

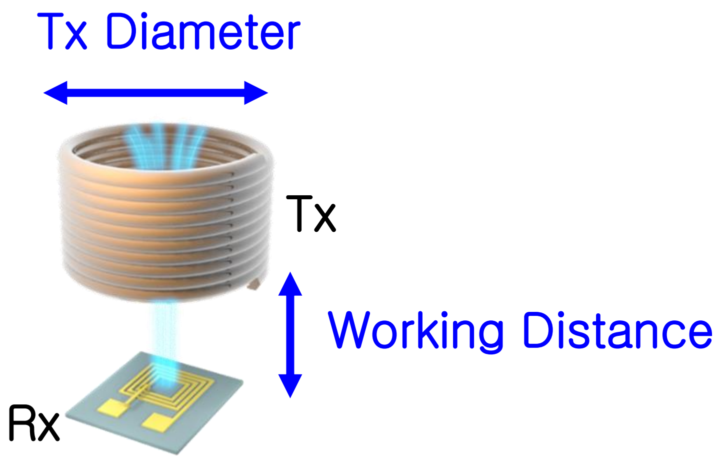


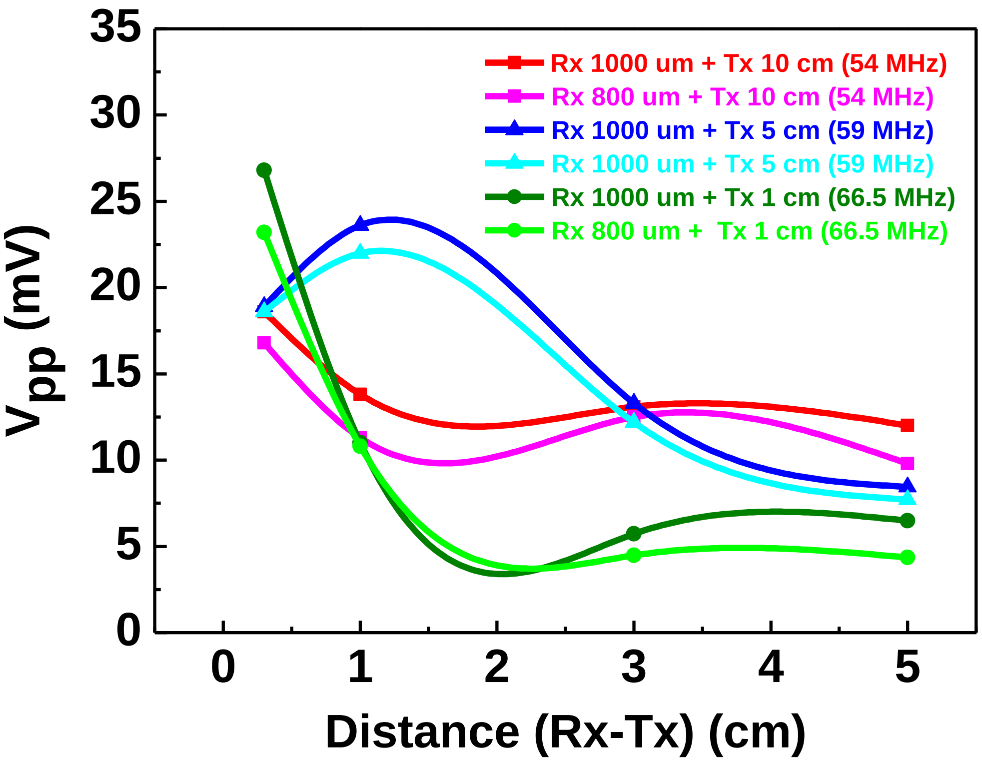
Solenoid coil #2
Diameter ***5 cm***
Coil thickness 0.1mm
17turn (height 2cm)



Solenoid coil #3
Diameter ***1 cm***
Coil thickness 0.1mm
17turn (height 2cm)

Geometry Effect of Transmission Coil (Tx)



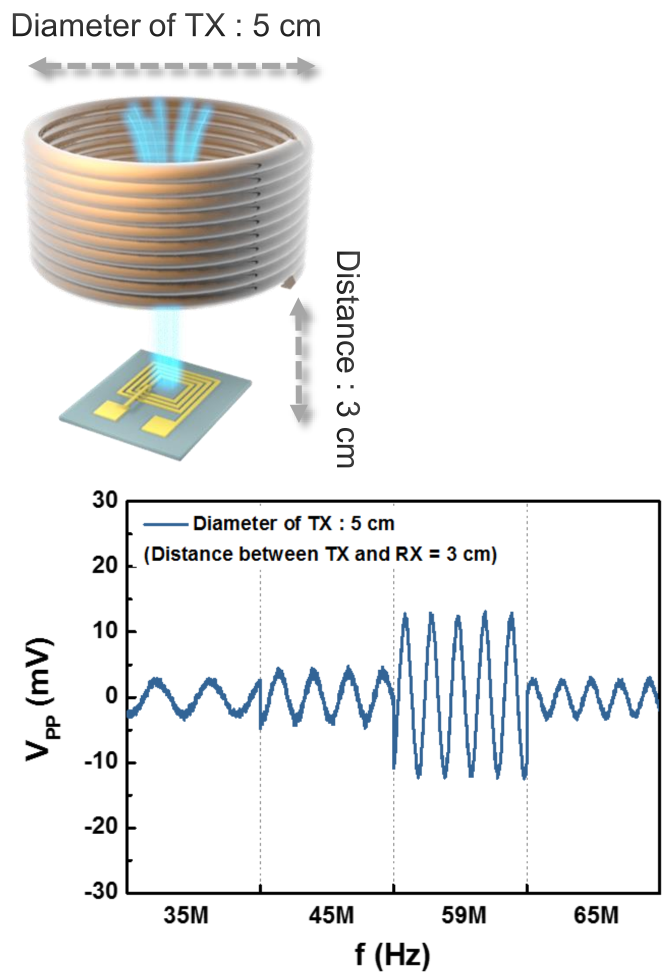


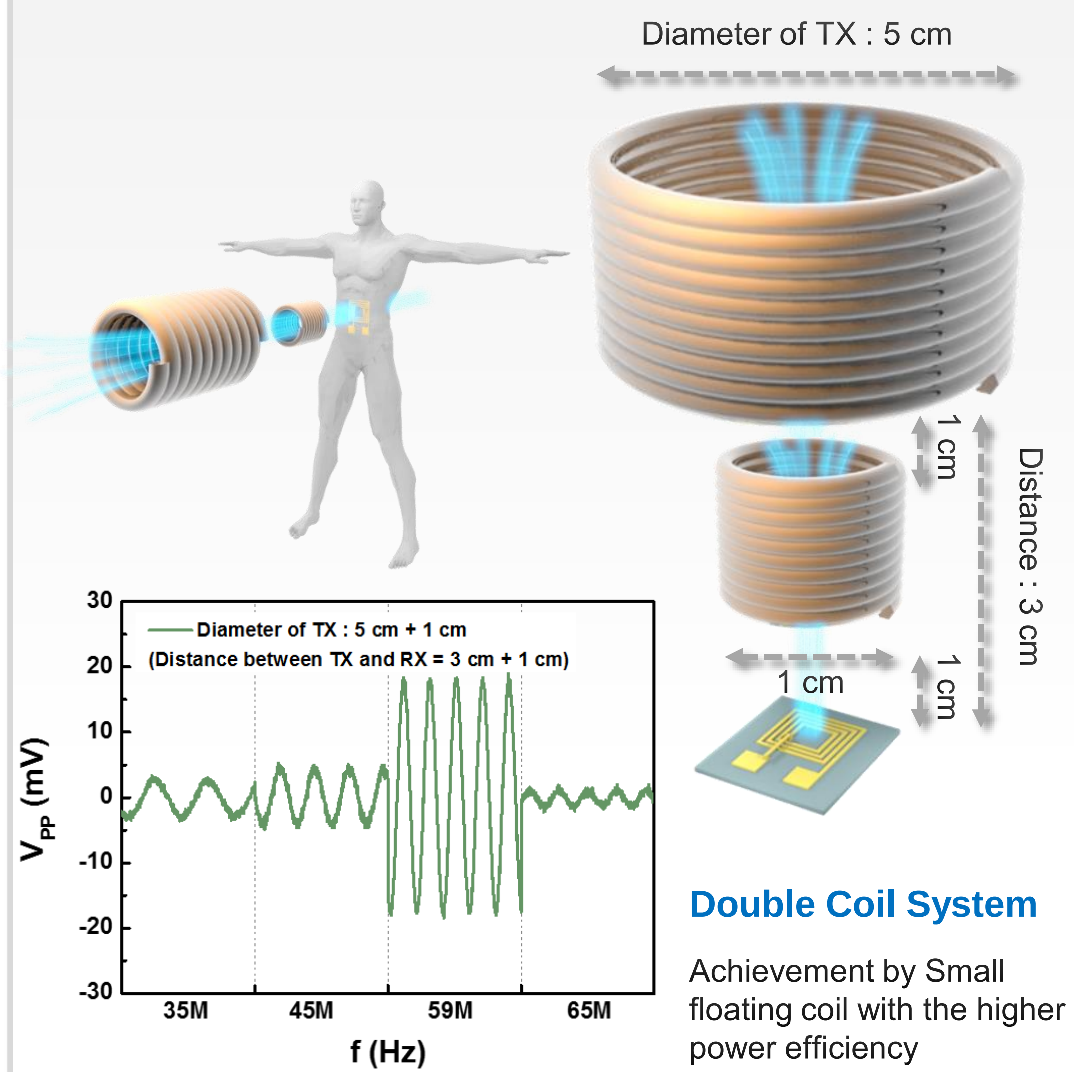
Geometry effect of transmission (TX) coil for micro size magnetic induction coil

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

K, H. Lee, *et.al.* , "A study on geometry efrfect of transmission coil for micro size magnetic induction coil" , ***Solid-State Electronics***, 119, (2016)

Multi-Tx concept

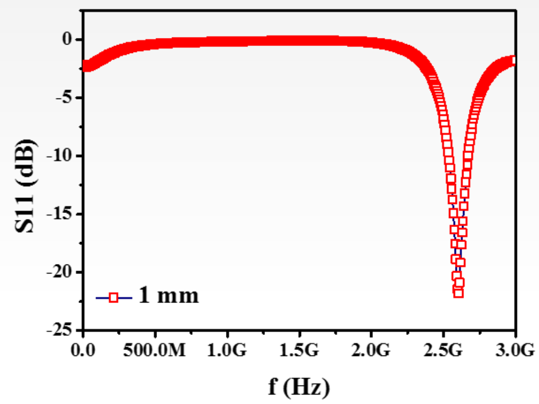




Double Coil System

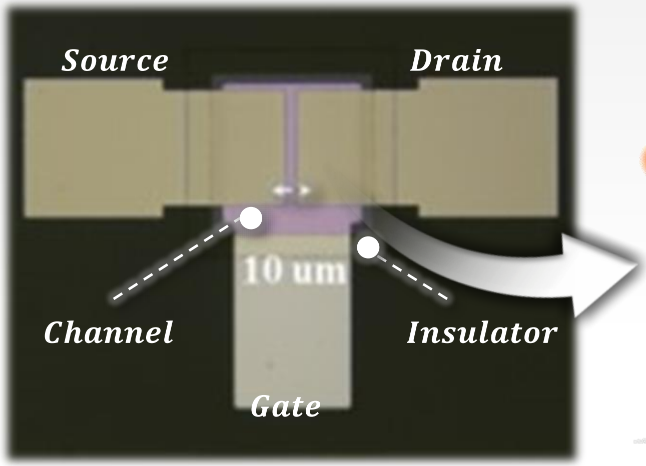
Achievement by Small floating coil with the higher power efficiency

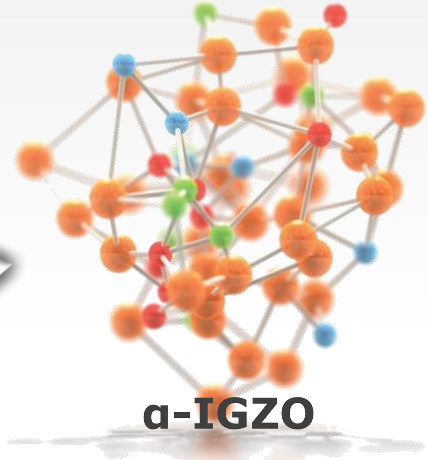
Issues of Thin Film Transistor (TFT)



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

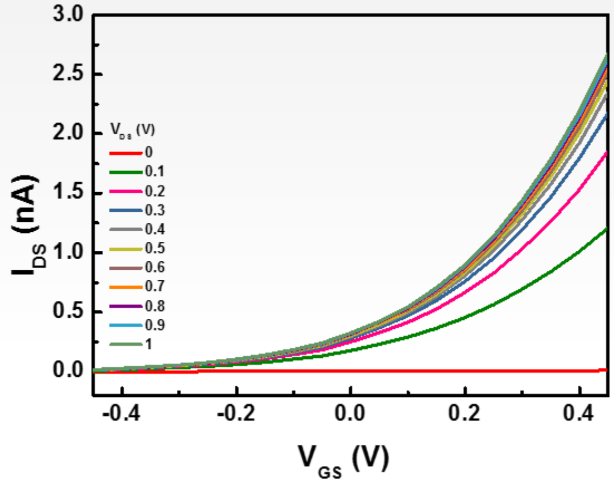
1. Requirement to drive the TFT at high frequency
2. An amorphous indium gallium zinc oxide TFT (α-IGZO TFT) structure, which shows higher mobility than an α-Si TFT

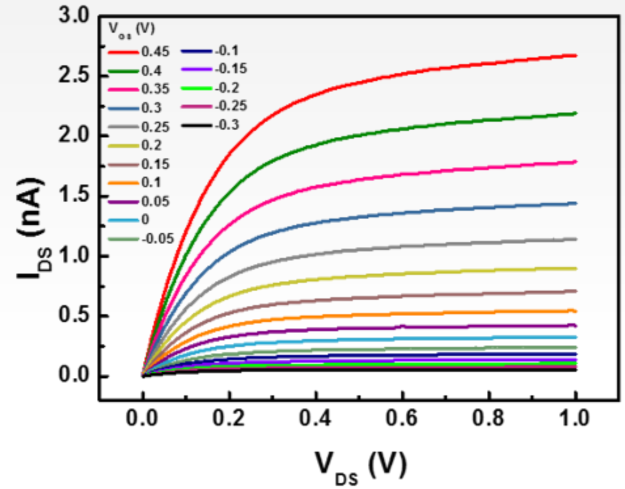
Advanced Electronic Device Research Group

Characteristics of a-IGZO TFT

TFT Features and The Performance

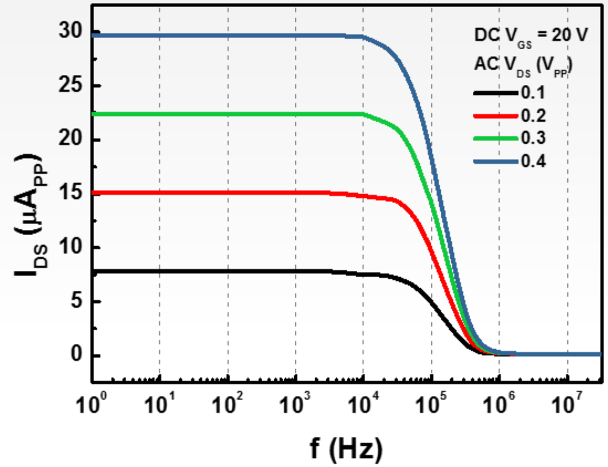
1. Wc(100 μm), Lc(10 μm), and Ci(17.4 nF)
2. Corresponding field-effect mobility $\mu_{FE(sat)}$: 13 cm^2/V_s
3. The following on-off ratio was about ~10^7

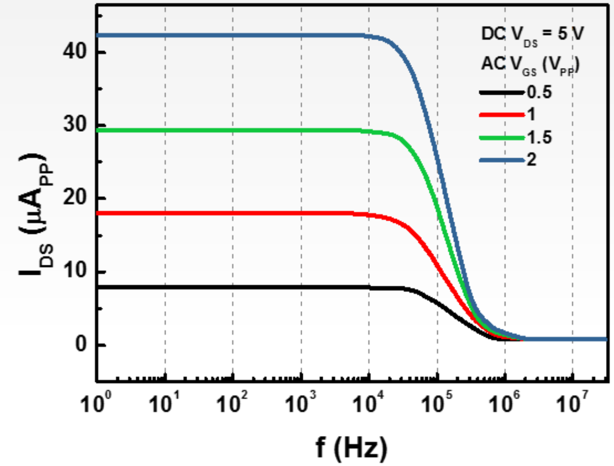




Frequency Response

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

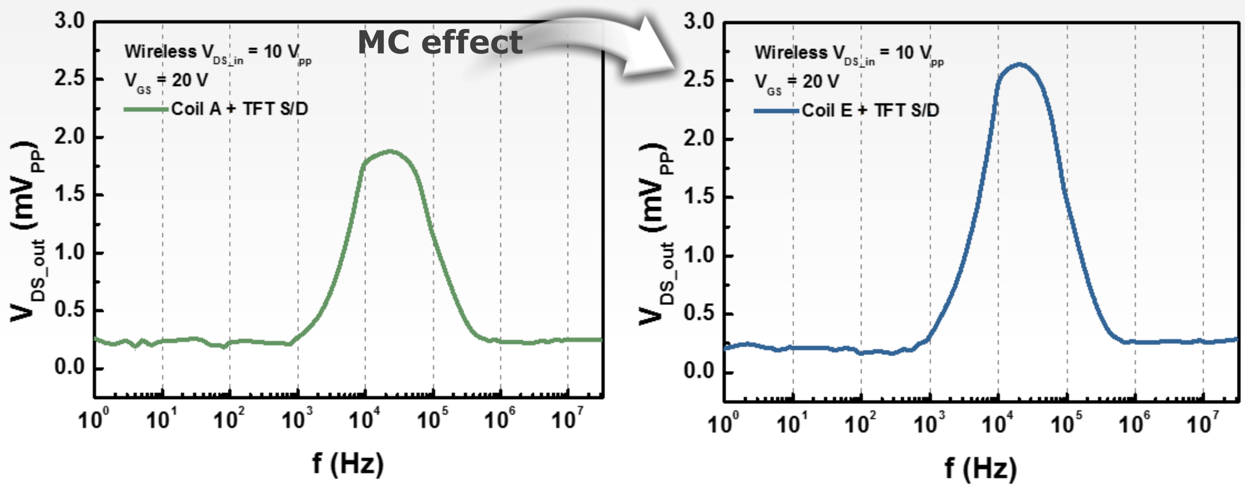




Wireless signal transmission in TFT (Antenna connection to S-D)

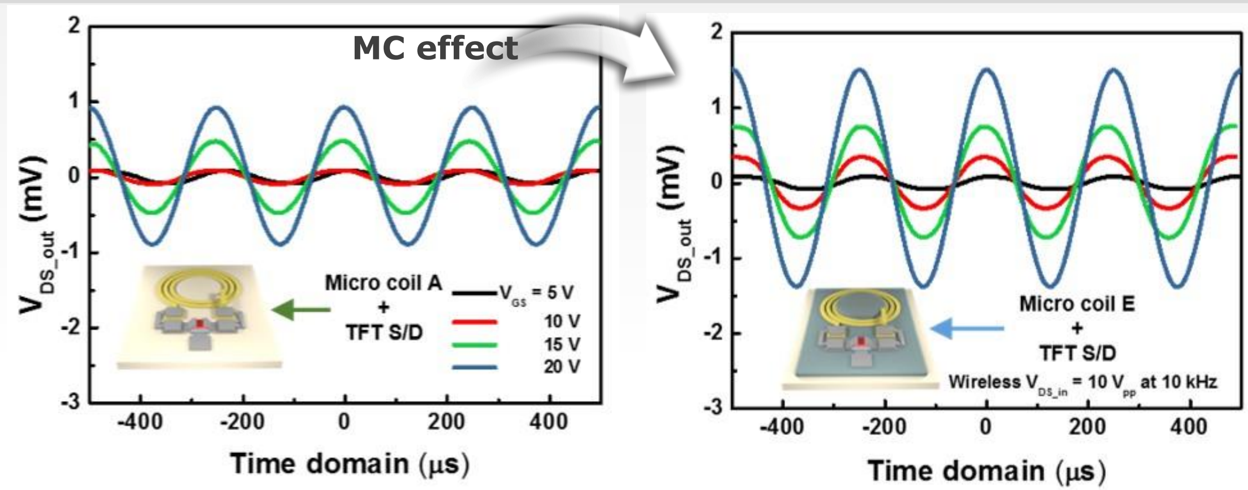
Frequency characteristics

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



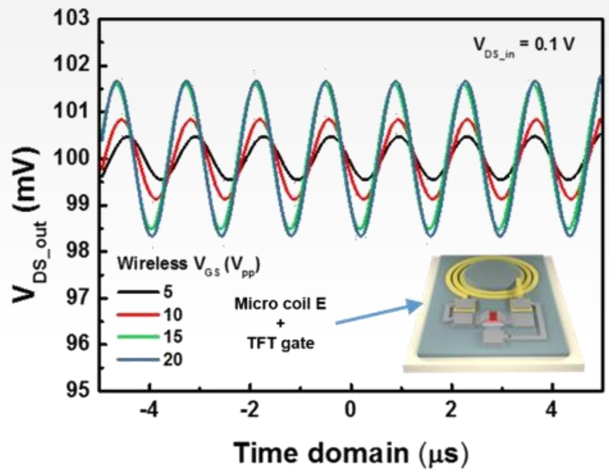
B. O. Jun, *et.al.*, "Wireless thin film transistor based on micro magnetic induction coupling antenna" , ***Scientific Reports***, 5, (2015)

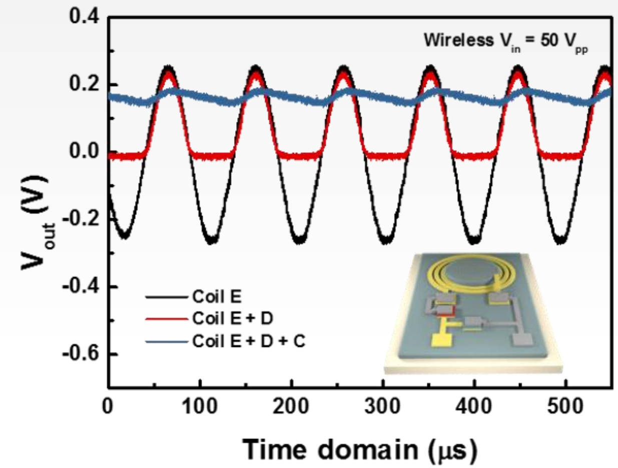
AEDRG Advanced Electronic Device Research Group

Wireless switching effect of TFT (Antenna connection to Gate)

Rectifying characteristics

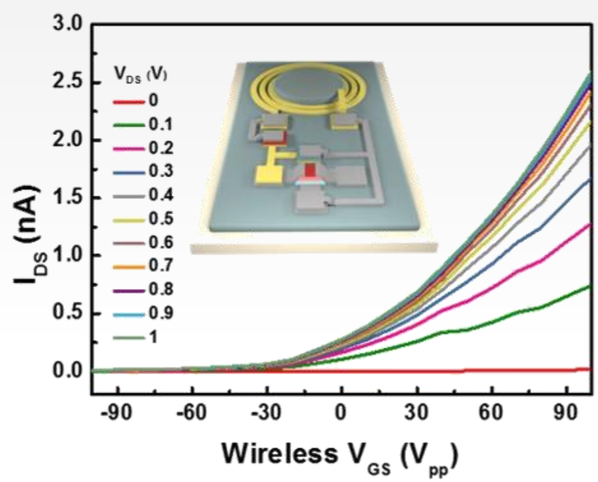
1. The out voltage difference at 20 VPP of TX antenna swing : About 3.4 mV
2. The rectified voltage through the Schottky diode and capacitor : About 0.2 V

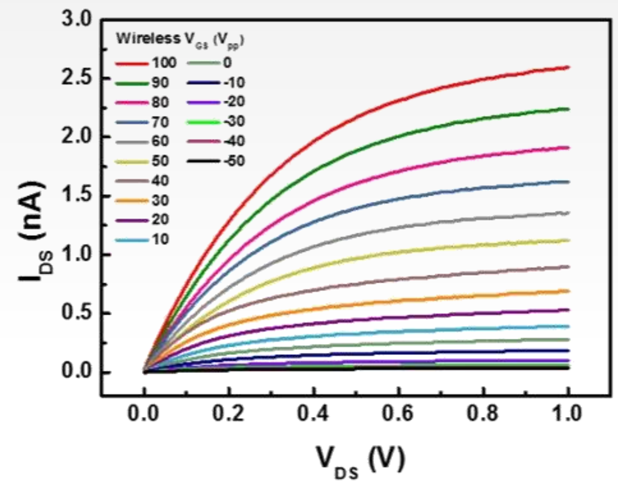




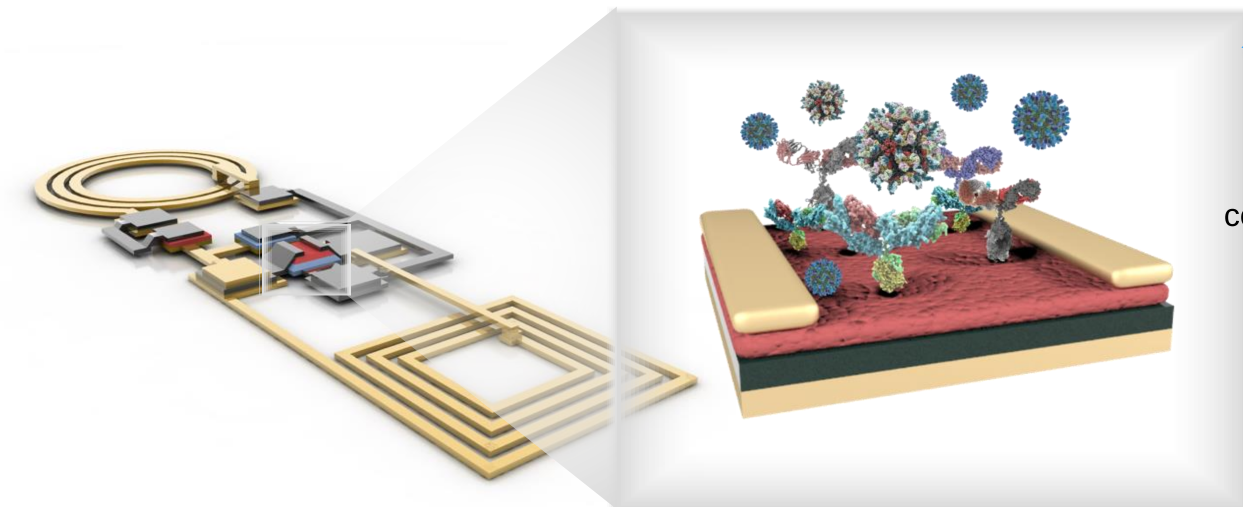
Electrical characteristics

1. Well controllable wireless TFT by wireless gate voltage
2. The corresponding on-off ratio is about ~10^3





Future applications

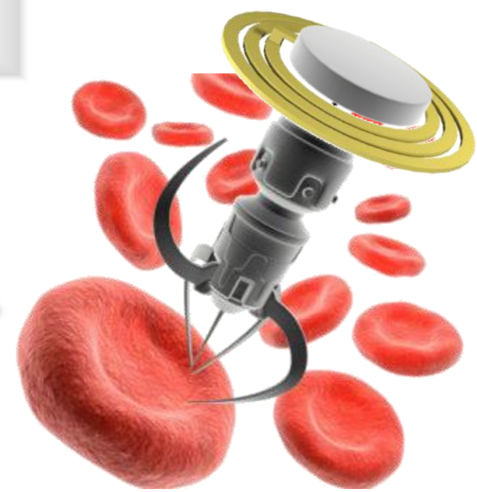


Wireless micro-miniaturized bio sensor

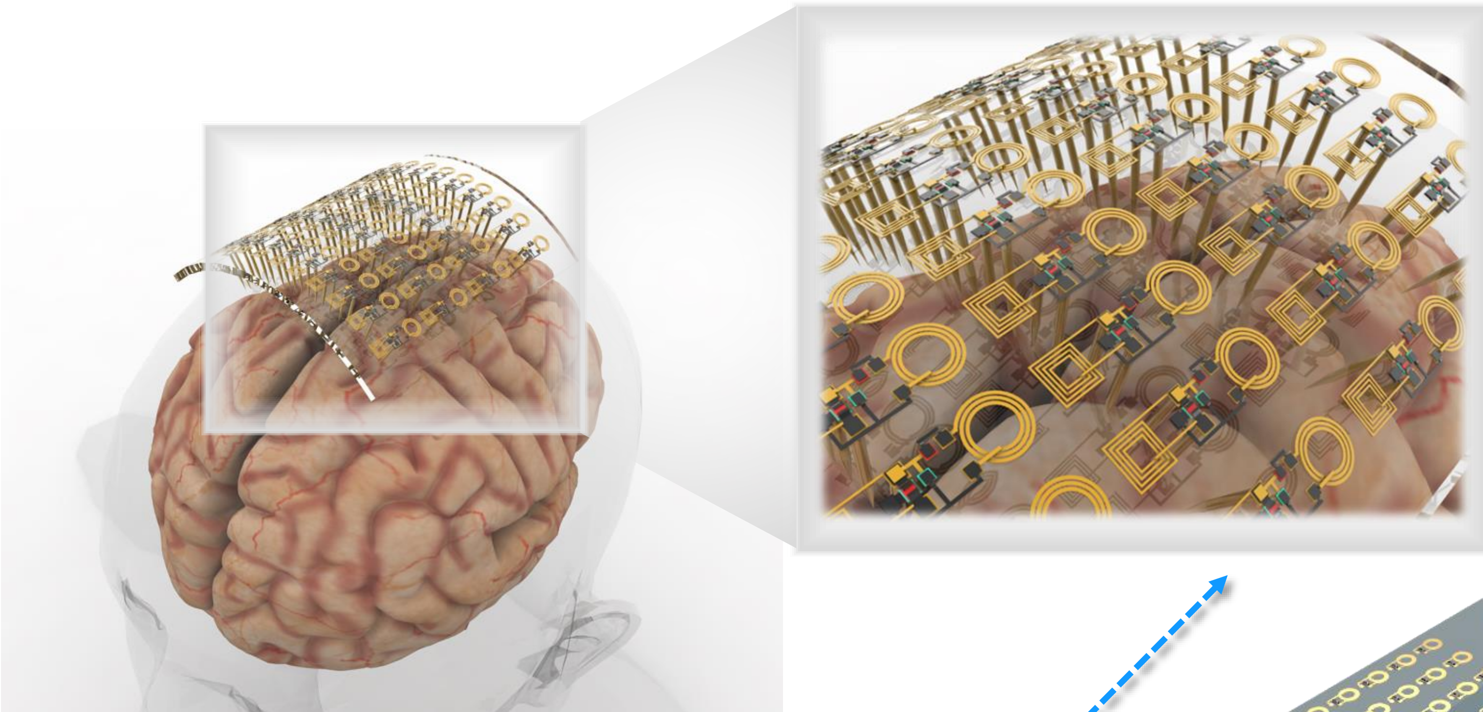
Detection of bio molecules in more confined and smaller spaces and wireless transportation of the information

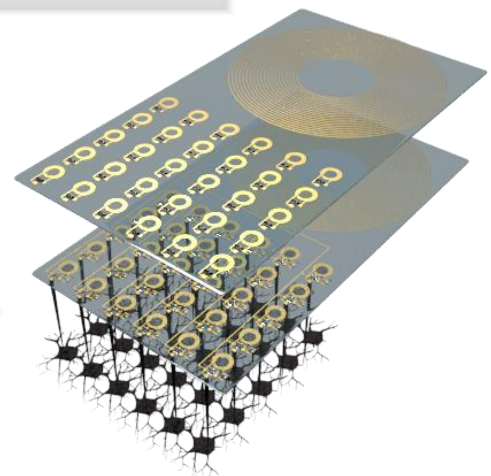
Micro-robot System

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