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High-Throughput Thermal Plasma Synthesis of FeCo Nano-Chained Particles with Unusually-High Permeability, and their Electromagnetic Wave Absorption Properties

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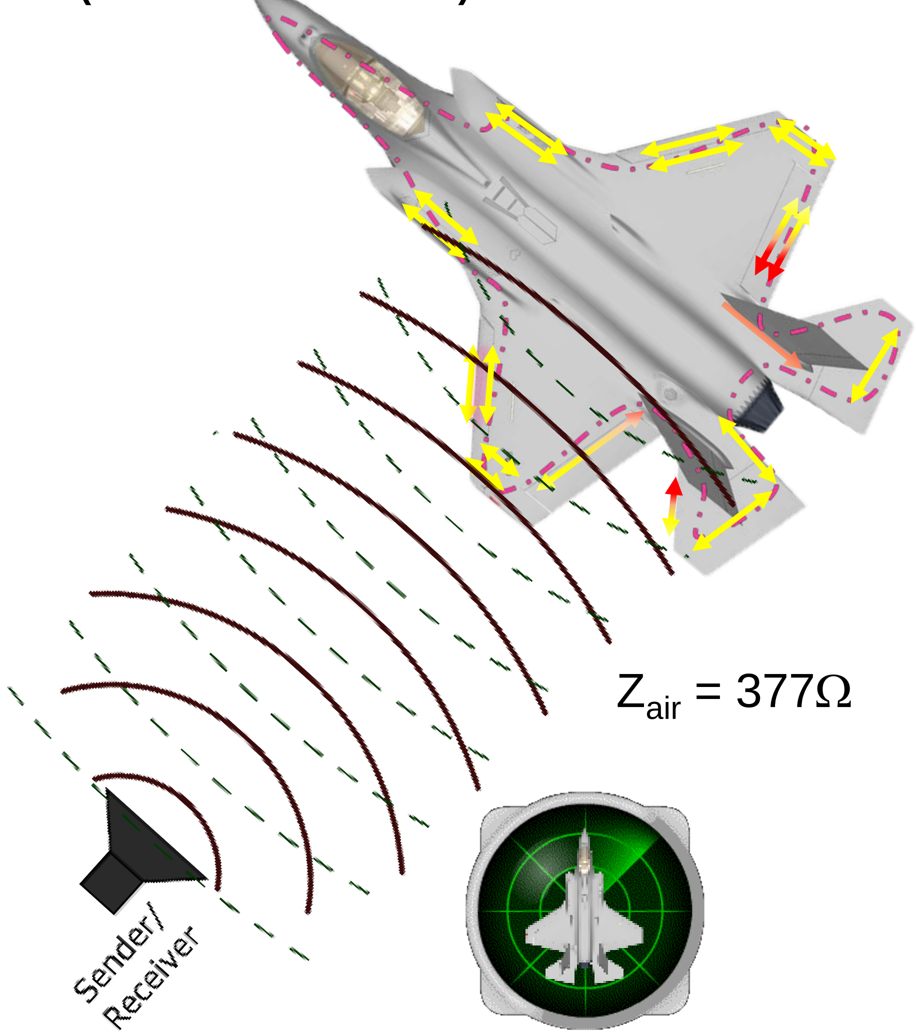
chapter 01

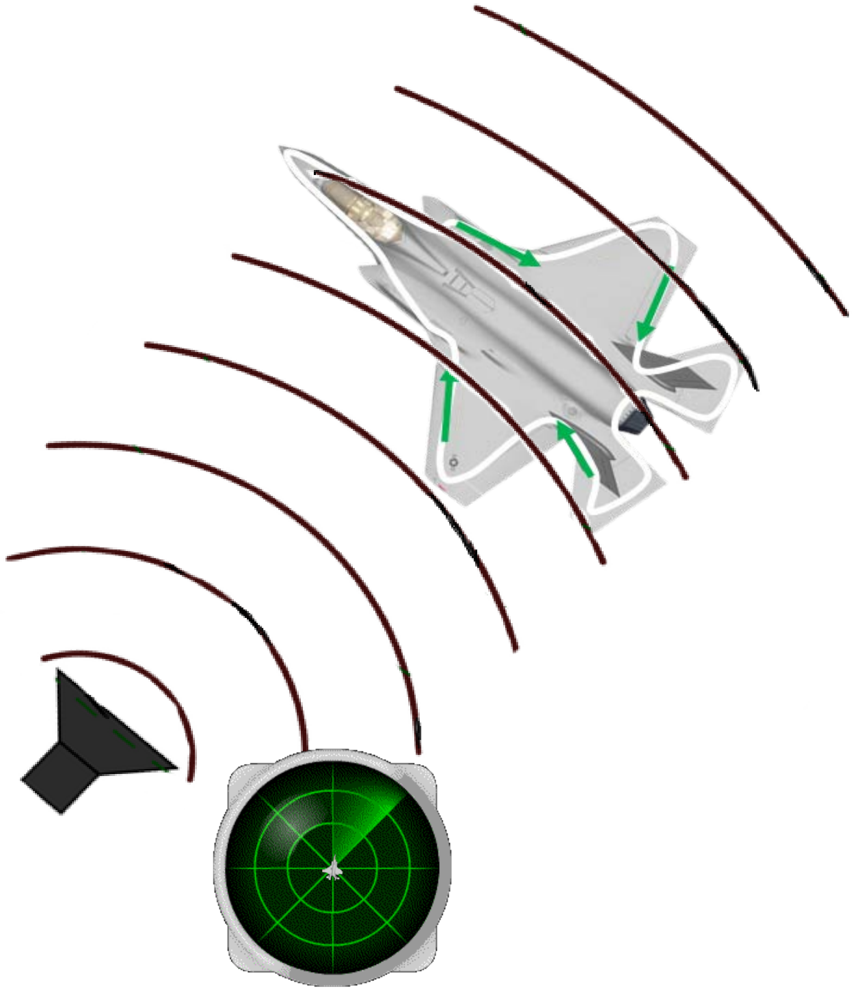
Introduction to EWAM

Introduction – Impedance Matching

Impedance mismatching
⇨ reflection increasing
⇨ RCS (Radar Cross Section) increase

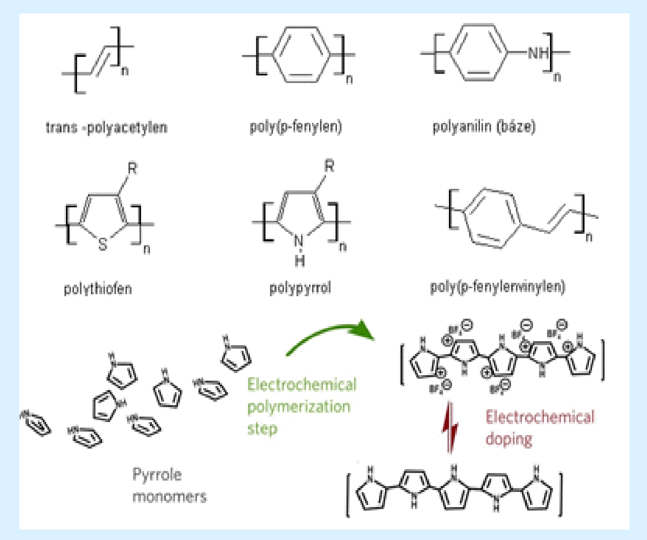


Impedance matching with RAM
⇨ reflection decrease
⇨ RCS decrease

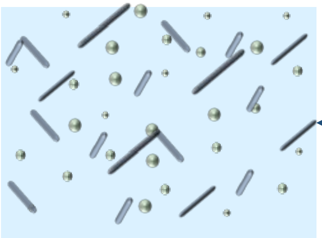


Introduction – Important Properties for RAM

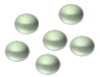
- ❑ Development of lightweight, ultrathin, broadband RAM ➾ Decrease in RCS(Radar Cross Section)
  - Impedance matching through high permeability magnetic particles + controlling micro-dielectric network structure
- ❑ Development of excellent durability (heat resistance, interfacial strength) and compatible materials ➾ Applications in future stealth and weapons technology
  - Heat-resistant epoxy resin used in CFRP (carbon fiber reinforced plastic) is applied



Heat-resistant/conductive polymer



Magnetic/dielectric particle composite material
(Nano-carbon network structure)

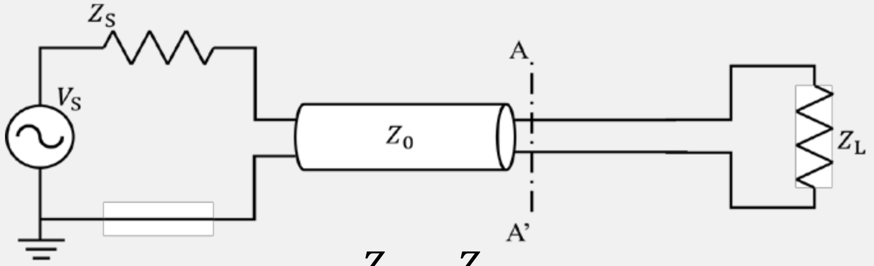


Magnetic particles

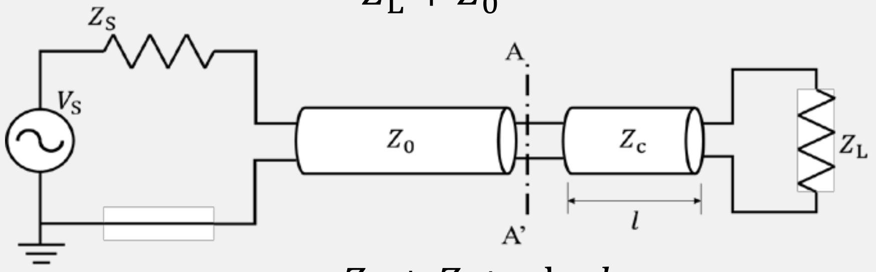
Carbon nanotubes

Introduction – Transmission Line Theory

Transmission Line Theory

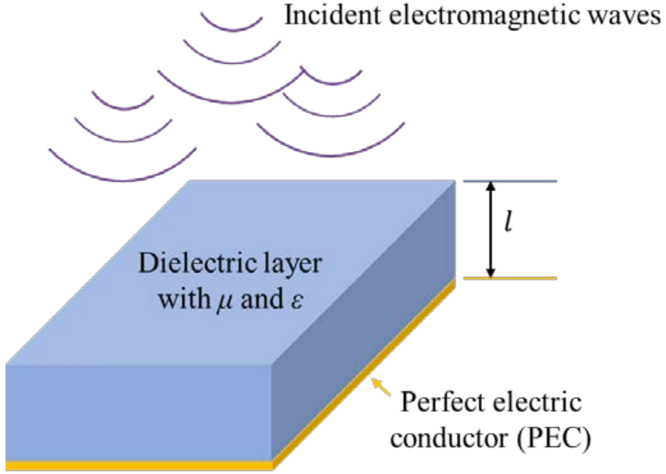


$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$



$$Z_{in} = Z_c \frac{Z_L + Z_c \tanh \gamma l}{Z_c + Z_L \tanh \gamma l}$$

γ = propagation constant



$$Z_L = 0$$

$$Z_{in} = Z_c \tanh \gamma l$$

$$Z_c = Z_0 \sqrt{\mu_r / \varepsilon_r} \qquad Z_0 = Z_{Air} = 377\Omega$$

$$\gamma = \mathrm{j} 2\pi f \sqrt{\mu_r \varepsilon_r} / c$$

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left(\mathrm{j} \frac{2\pi f \sqrt{\mu_r \varepsilon_r} l}{c}\right)$$

$$= Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \mathrm{j} \tan\left(\frac{2\pi f \sqrt{\mu_r \varepsilon_r} l}{c}\right) = Z_0 = 377\ \Omega.$$

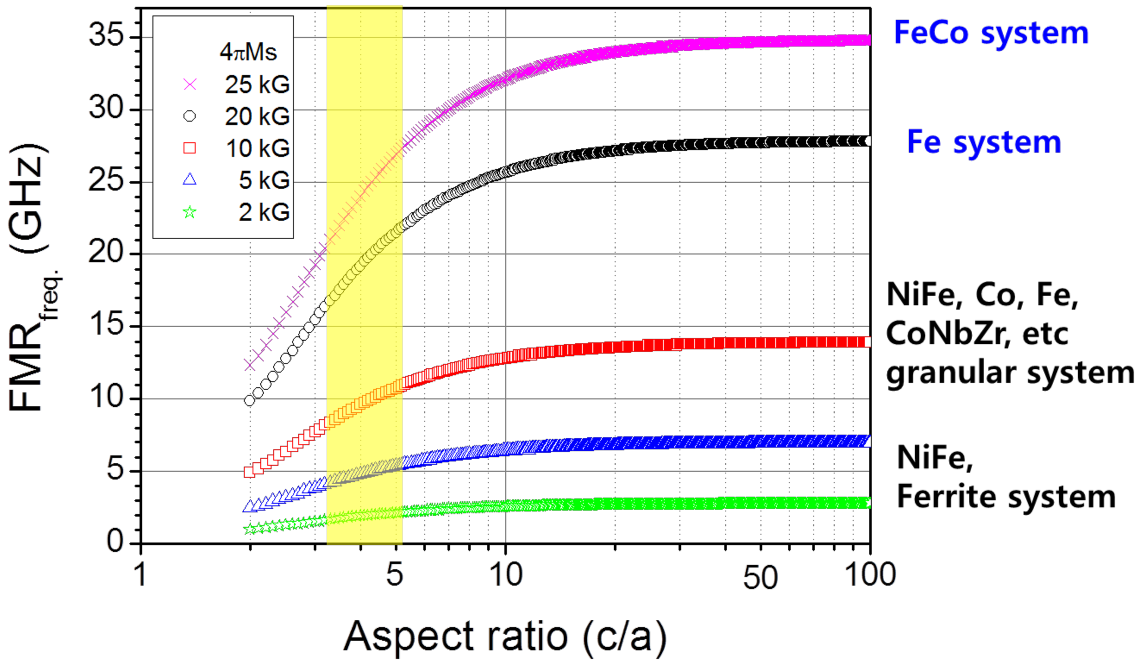
Introduction – Development of magnetic particles with high permeability

❑ **When designing a new magnetic material intended for broadband electromagnetic wave absorbing material (EWAM) properties, the following conditions should be met:**

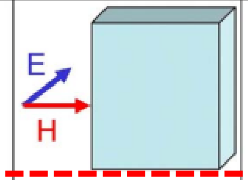
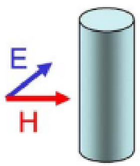
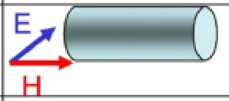
(1) High saturation magnetization

(2) Structural anisotropy for higher magnetic anisotropy

(3) Modulated permittivity for impedance matching



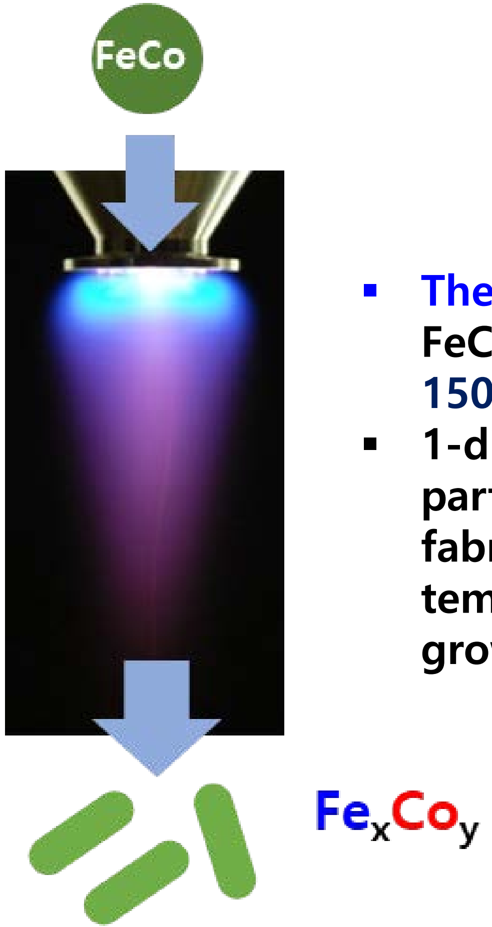
Change in FMR according to the saturation magnetic flux density and aspect ratio of magnetic particles

inclusion type	sketch	$A(ka)$	2^{nd} order approx.
plate		$\frac{\tan(ka)}{ka}$	$1+\frac{(ka)^2}{3}$
cylinder $\perp$ H		$\frac{J_1(ka)}{ka.J_0(ka)-J_1(ka)}$	$1+\frac{(ka)^2}{4}$
cylinder // H		$\frac{2J_1(ka)}{ka.J_0(ka)}$	$1+\frac{(ka)^2}{8}$
sphere		$\frac{2(\tan(ka)-ka)}{ka+((ka)^2-1)\tan(ka)}$	$1+\frac{(ka)^2}{10}$

Improvement in permeability through powder shape control
(O. Acher et al., 2007)

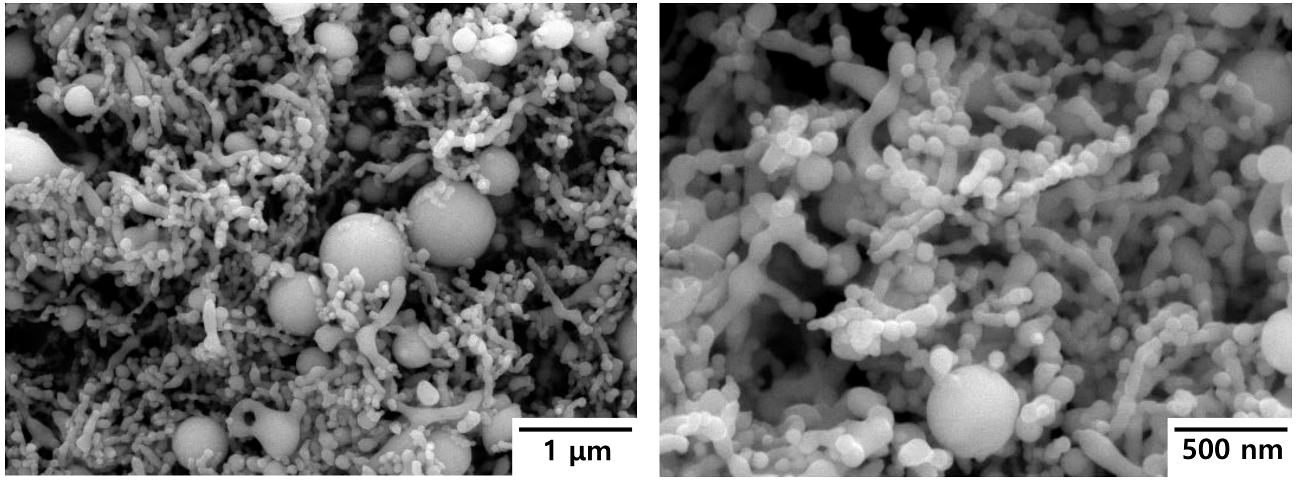
Introduction – Development of magnetic particles with high permeability

❑ Synthesis of magnetic nanorod particles through thermal plasma



- Thermal Plasma synthesis of Fe, FeCo nanoparticles (6000 ~ 15000 K)
- 1-dimensional nano-chained particles were successfully fabricated without need for templates or complex directional growth process.

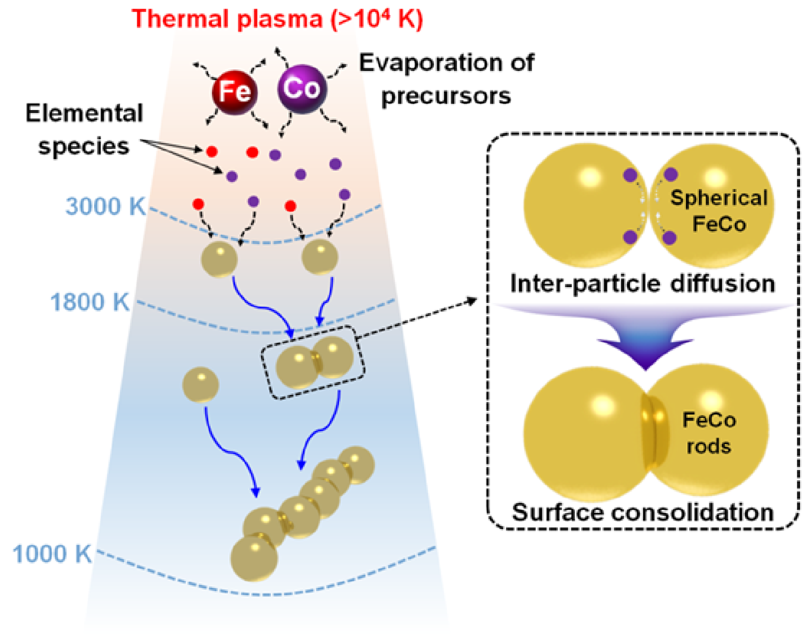
Fe-Co nanorods



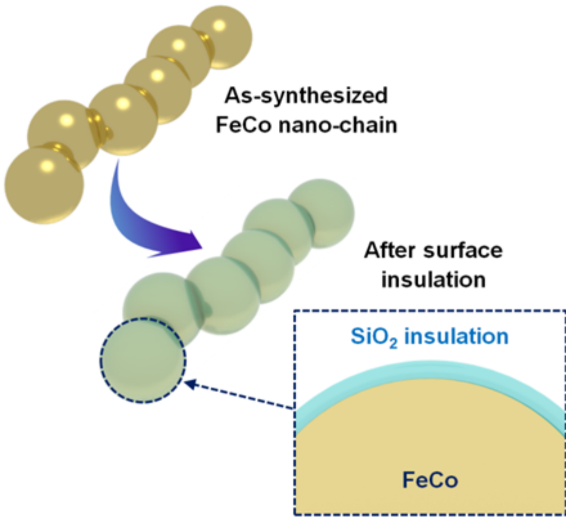
chapter 02

Results and Discussion

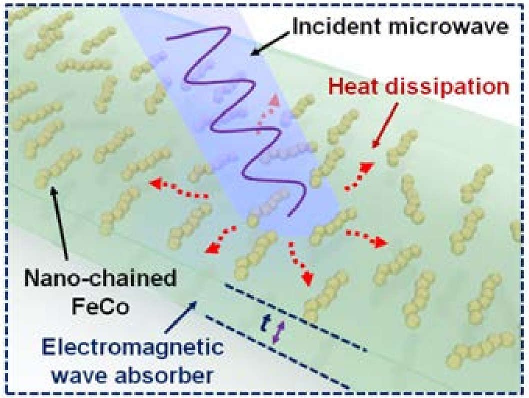
Results & Discussion



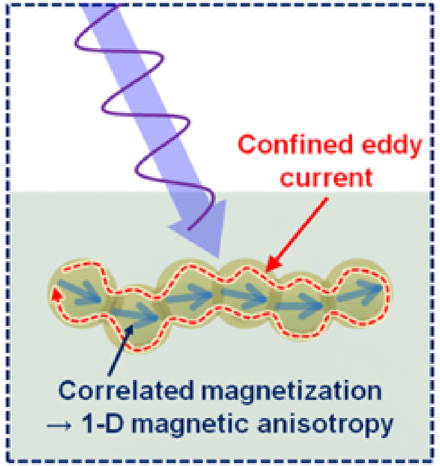
Below 1800 K, diffusion occurs between inter-particle to form rod-like shapes.



Enclosed insulating surface

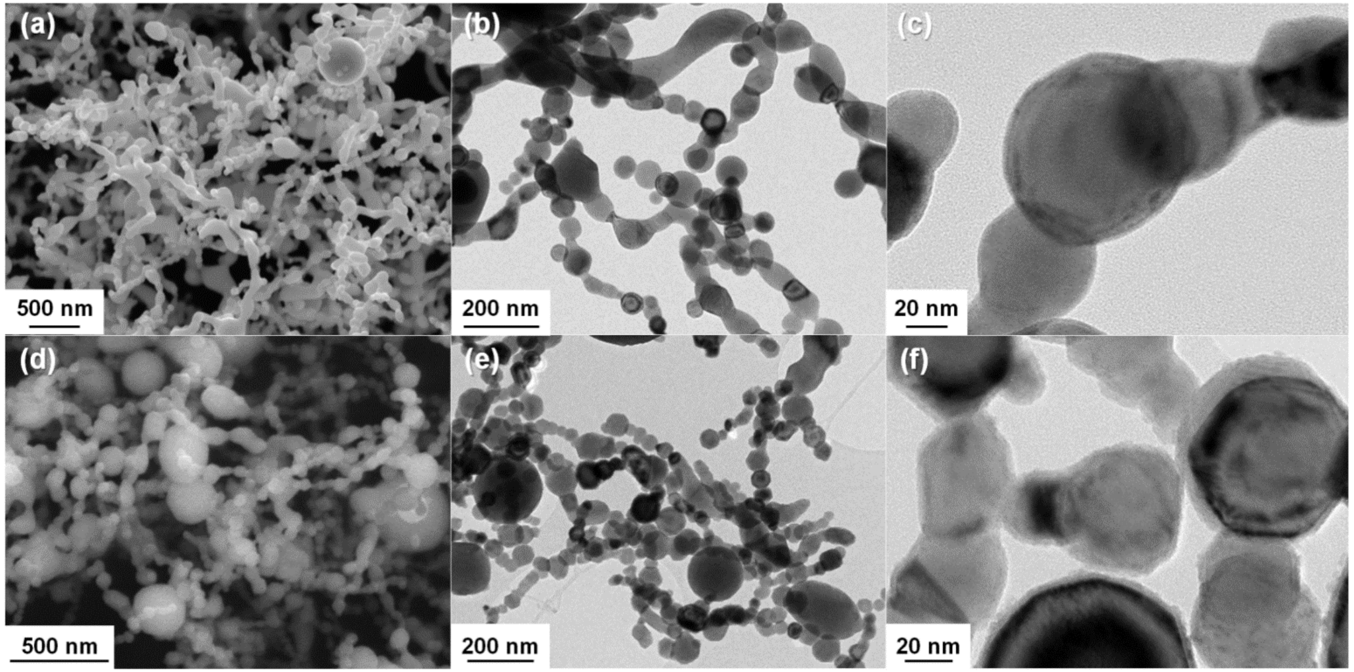


Heat dissipation of incident microwave irradiated on electromagnetic wave absorber embedded nano-chained FeCo.

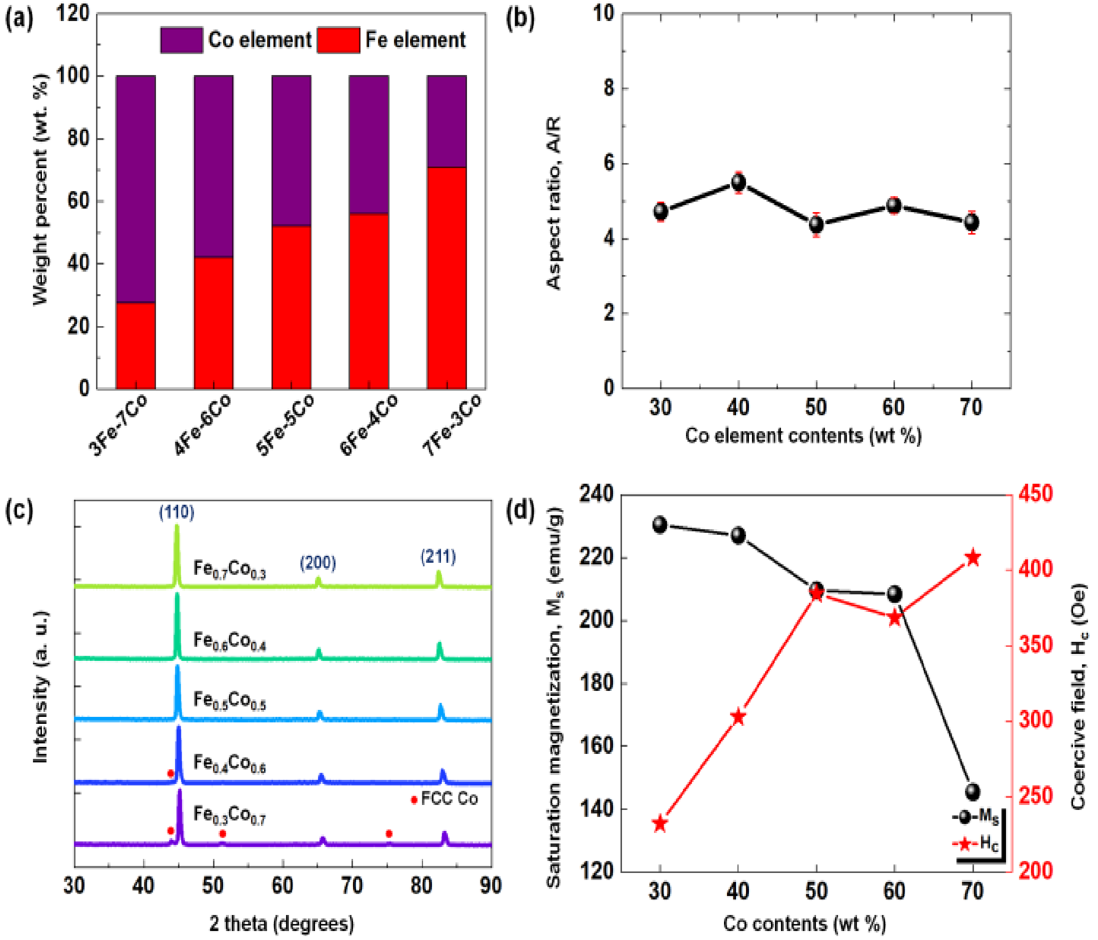


Eddy current formation for 1-D magnetic anisotropy formed in FeCo chains.

Results & Discussion



Transmission electron microscope (TEM) images of nano-chained Fe_xCo_{1-x} synthesized by RF-ITP: (a) - (c) x= 0.6 and (d) - (f) x= 0.3.



(a) Graph of combined appropriate weight ratio of Fe to Co, *i.e.* 7:3 to 3:7. (b) Graph of distinctive aspect ratio versus composition with varying weight ratios of Fe to Co, i.e. 7:3 to 3:7, calculated from regions in images. (c) Powder X-ray diffraction (XRD) patterns of Fe_xCo_{1-x} alloys (x=0.3, 0.4, 0.5, 0.6, and 0.7). All of the prominent peaks, including (110), (200), and (211), correspond to those of FeCo with bcc structure. (d) Magnetic properties identified for various weight percents of Co elements. Saturation magnetization, M_s (black color), and coercive field, H_c (red color), measured by VSM at room temperature.

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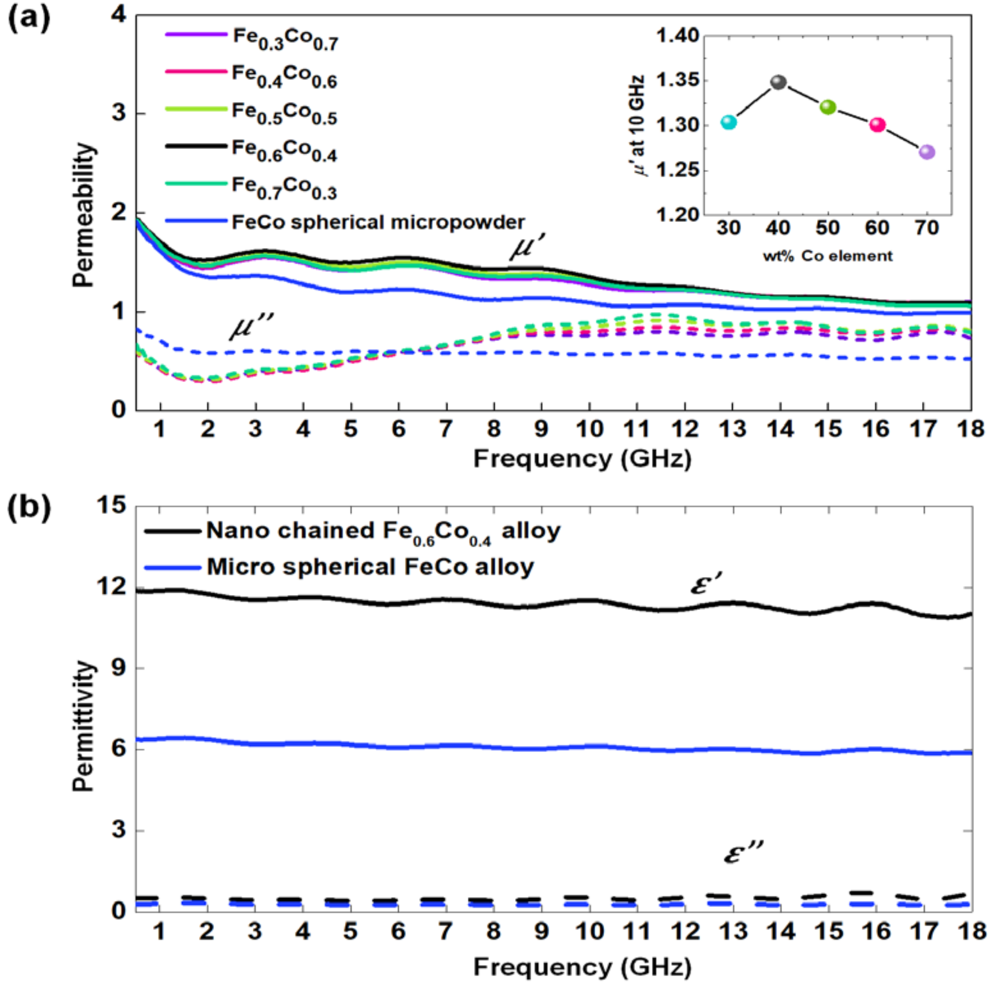
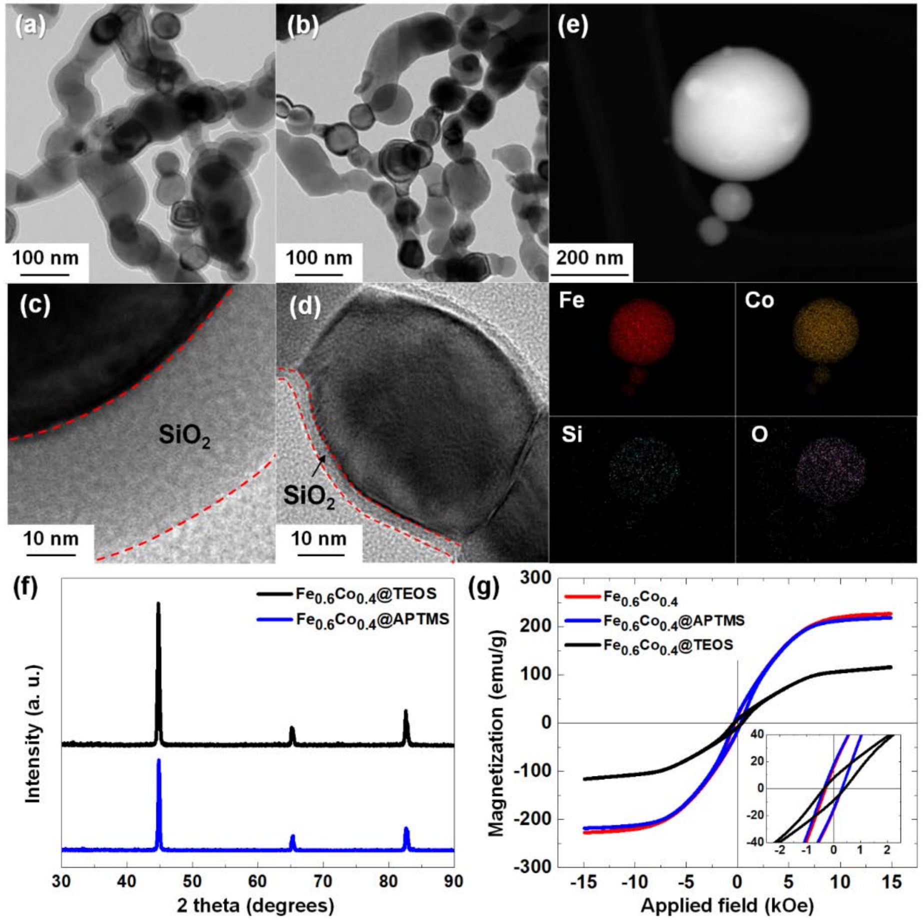
Results & Discussion

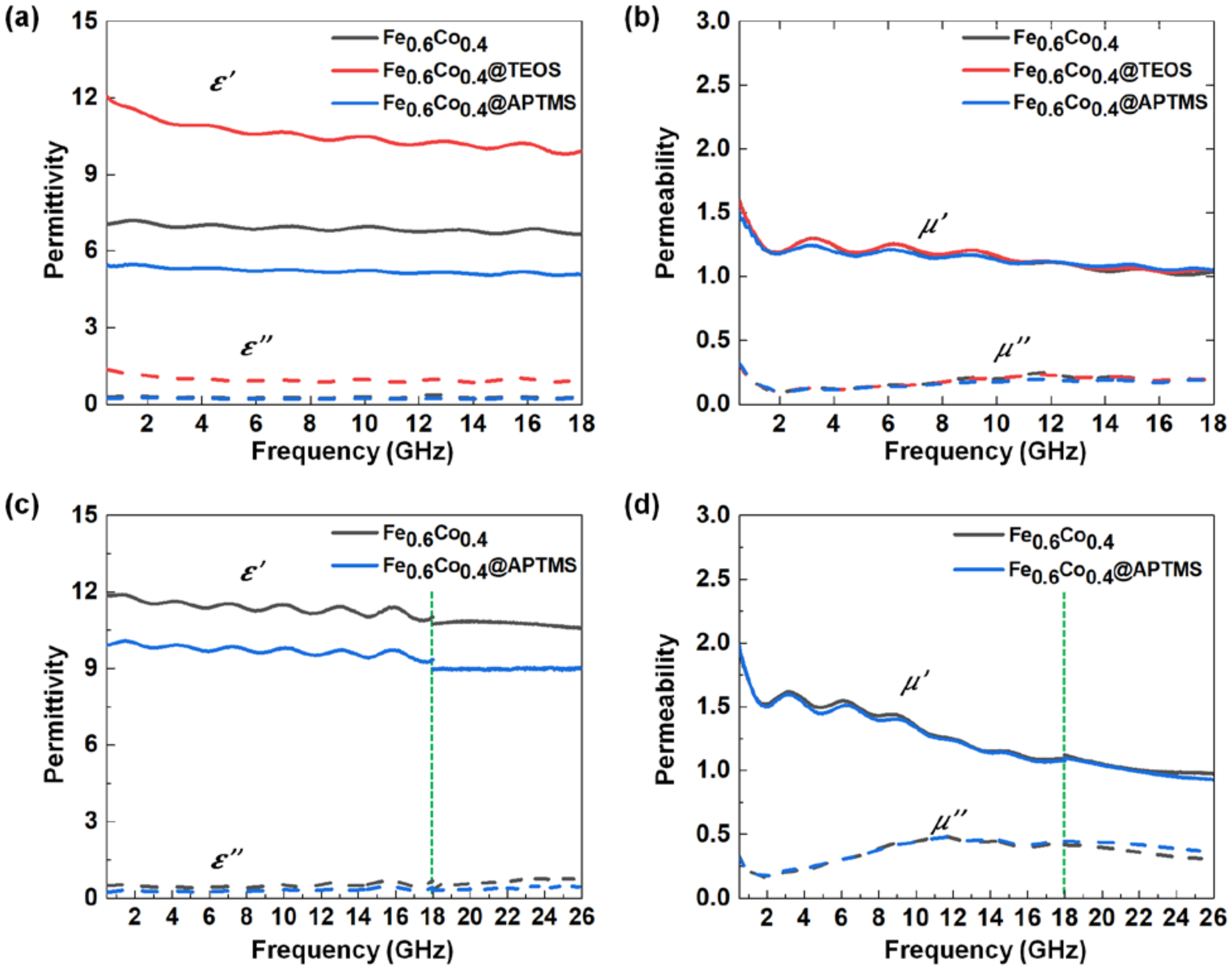


(a) Complex permeability of nano-chained Fe_xCo_{1-x} and FeCo spherical micro powder. (b) Complex permittivity of $Fe_{0.6}Co_{0.4}$ nano-rods and FeCo spherical micro powder.



TEM images at different magnifications of insulation coated $Fe_{0.6}Co_{0.4}$: 100 nm scale, (a) and (b); 10 nm scale, (c) and (d). Individual coating materials show different thicknesses of SiO_2 of 29.21 nm and 2.00 nm, respectively. (e) TEM image of $Fe_{0.6}Co_{0.4}$@APTMS and corresponding energy dispersive X-ray image obtained using EDS element mapping analysis. (f) XRD patterns of $Fe_{0.6}Co_{0.4}$@TEOS and $Fe_{0.6}Co_{0.4}$@APTMS. The well-defined peaks reveal the degree of crystallinity after coating. (g) Magnetic hysteresis loop of $Fe_{0.6}Co_{0.4}$, $Fe_{0.6}Co_{0.4}$@TEOS, and $Fe_{0.6}Co_{0.4}$@APTMS; inset shows corresponding low-field H_c values.

Results & Discussion



(a) Complex permittivity and (b) complex permeability of different condition samples of $Fe_{0.6}Co_{0.4}$: as synthesized, @TEOS, and @APTMS. The widened frequency dependence of complex permittivity (c) and complex permeability (d) of $Fe_{0.6}Co_{0.4}$: as synthesized and @APTMS.

Results & Discussion

Electromagnetic wave absorbing performance is evaluated by calculating their reflection loss (RL) at various thicknesses *d* and frequencies *f*, which can be calculated as follows with the measured $\boldsymbol{\mu}_{\mathbf{r}}$ and$\boldsymbol{\varepsilon}_{\mathbf{r}}$:

$$\boldsymbol{Z}_{\mathbf{in}} = \boldsymbol{Z}_0 \sqrt{\frac{\boldsymbol{\mu}_r}{\boldsymbol{\varepsilon}_r}} \mathbf{tanh}\left(\boldsymbol{j}\frac{2\boldsymbol{\pi f d}}{\boldsymbol{c}}\sqrt{\boldsymbol{\mu}_r\boldsymbol{\varepsilon}_r}\right) \cdots\cdots\cdots\cdots\cdots (2)$$

$$RL = 20\log_{10}\left|\frac{Z_{\mathrm{in}} - Z_0}{Z_{\mathrm{in}} + Z_0}\right| \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Currently ongoing…

Conclusion

- High-purity FeCo nanoparticles with 1-dimensional chained shapes were prepared by highly-productive thermal plasma synthesis while using mixtures of Fe- and Co-elements as precursors.
- Systematic control of the composition and magnetic properties of Fe_xCo_{1-x} nano-chained particles has been accomplished by changing the mixing ratio (Fe-to-Co) of the precursors, *i.e.* 7:3 to 3:7. The highest M_s of 230.4 emu/g was obtained at the composition of $Fe_{70}Co_{30}$, while the aspect ratio of nano-chained FeCo was kept within 4-6.
- With high M_s of 227 emu/g and aspect ratio of 5.5, $Fe_{0.6}Co_{0.4}$ nano-chained particles exhibited overwhelmingly intensified complex permeability, 19.45% higher than that of $Fe_{0.6}Co_{0.4}$ spherical micro-particles.
- Precisely-controlled and uniform surface SiO_2 coating on FeCo nano-chained particles effectively modulated the complex permittivity. In particular, $Fe_{0.6}Co_{0.4}$@SiO_2 with 2.00 nm thickness provided optimally reduced permittivity, which opens possibilities of improved impedance matching.
- RL values will soon be measured.

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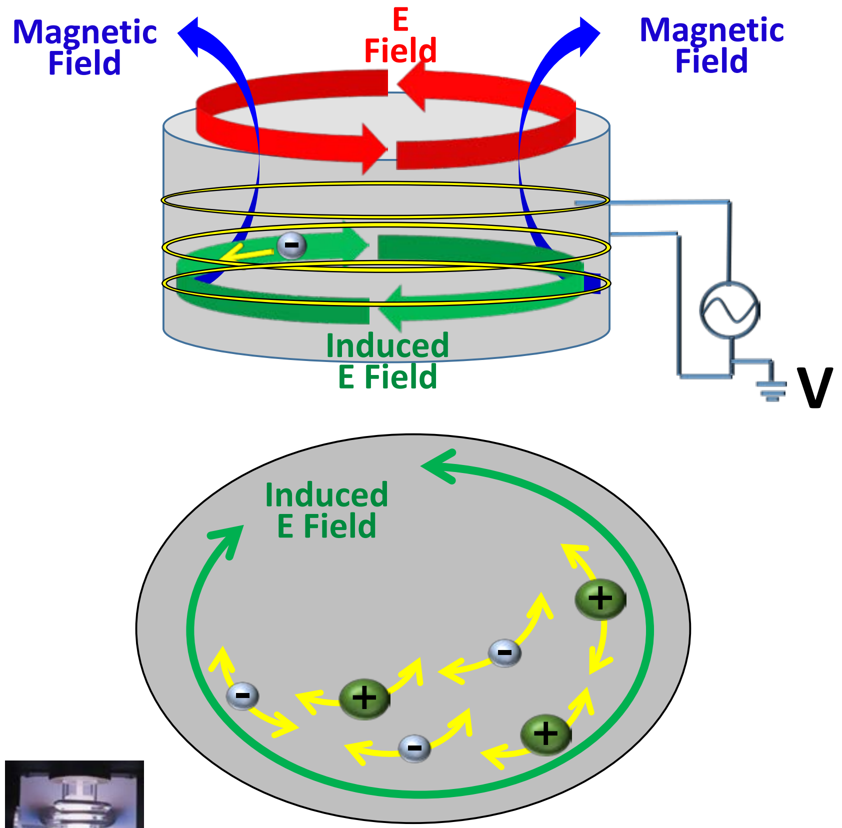
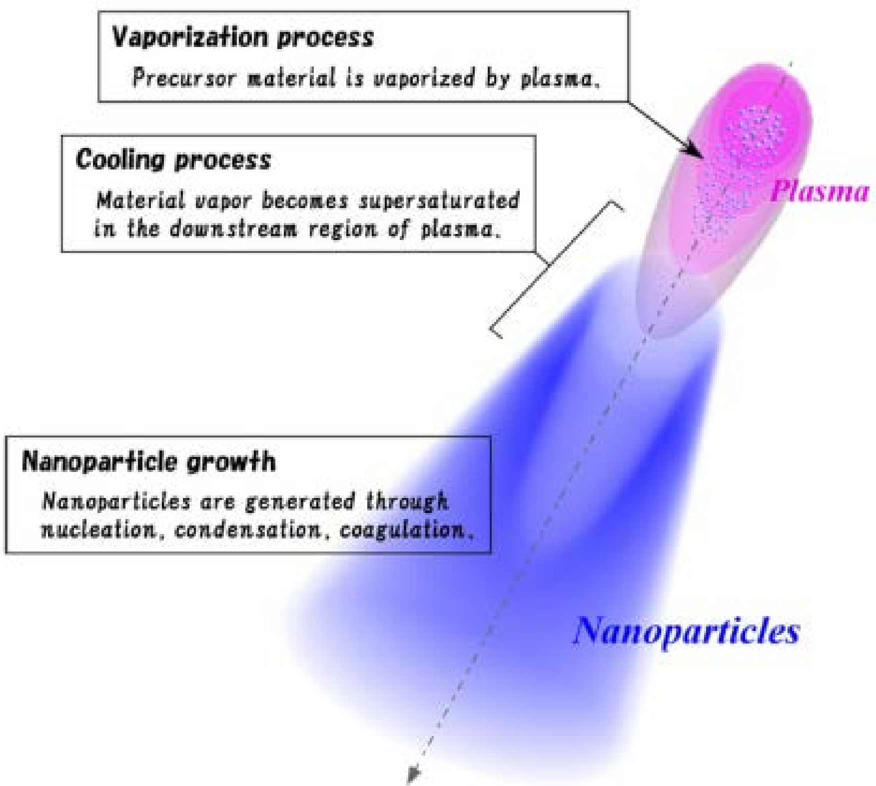
Thank You

Appendix

❑ Thermal Plasma

Inductively Coupled Plasma (ICP)





- **Thermal plasma**
  - Temperature: 6000 ~ 15000 K
    - Heavy particles possess temperature as high as 10^6~10^8 K while pressure is at atm.
- **Nanofabrication using RF-ICP**
  - Evaporation of precursor
  - Nanoparticle formation by condensation