RFHIC®

Applications of Microwave Heating with SSPA in Various Fields

RFHIC | sang-jin Kim Ph.D.

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CONTENTS

1.RFHIC company profile

Pioneers in GaN Solid-State Microwave

About RFHIC

A leading pioneer in designing and manufacturing GaN RF & Microwave components for various applications in wireless communications, defense & aerospace, and RF energy sectors.

RFHIC Stands For

RFHIC stands for **Radio Frequency Hybrid Integrated Circuit**.
RFHIC was founded in 1999, and it all started with an incurable need for cost-effective GaAs transistors and MMICs for satellite applications within South Korea.

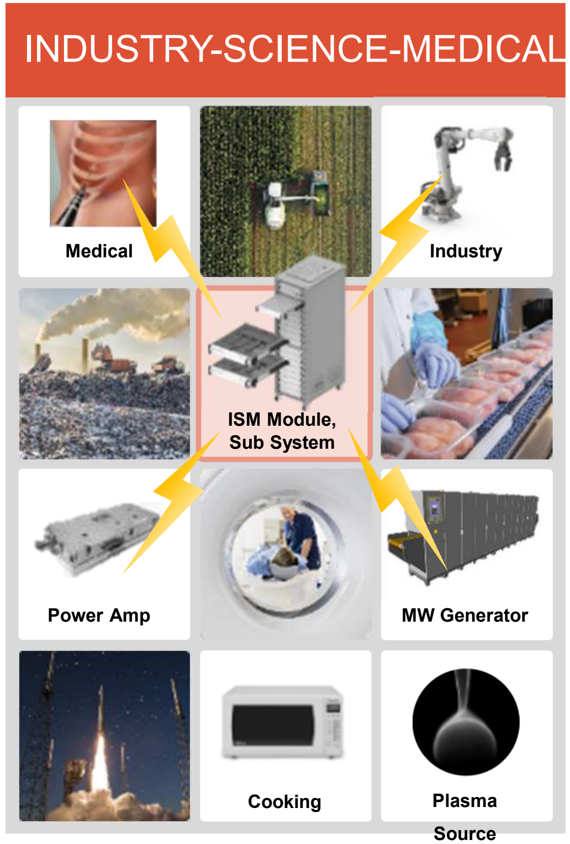
Reimagine what's possible

RFHIC's One-Stop GaN Solution Service

RFHIC can design and manufacture from device to sub-system level – all within our In-House Production Facility

Transistor Assembly	Transistor Testing	Power Amplifier Assembly	Sub-System Assembly	After Service Care
				
• Custom Transistor Pkg • In-house Grade 4 Clean Room Facility • Operable from DC-40GHz • Power Levels up to 1kW	• HTRB (High-Temperature • Reverse Bias) Age Testing • DC Testing • Ultrasound Testing	• In-house automated SMT line • Faster and Robust PA Assembly • Custom design capabilities	• Operable from 500MHz-10GHz • Power Levels Capable of up to Multi-KWs • Complete device to system-level replacement capabilities	• In-house device to system-level expertise • Faster service • Higher customer satisfaction and brand loyalty

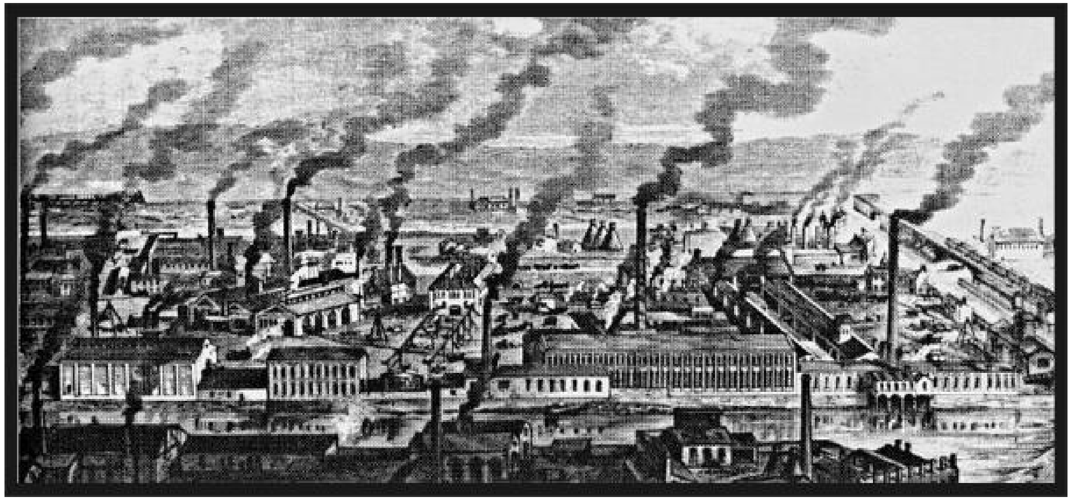
RFHIC Major Business Segments

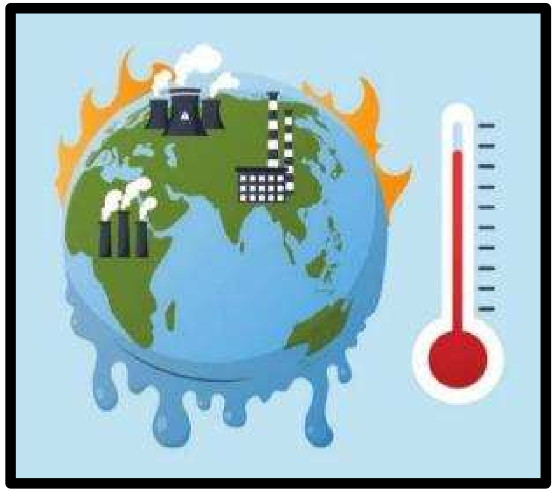


2. Why Microwave need to energy source ?

Climate change caused by industrial development

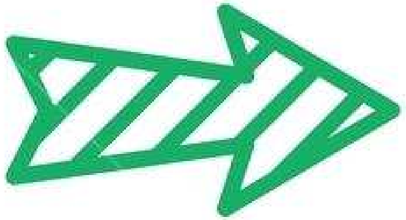
Since the industrial revolution, climate change has been caused by increased greenhouse gas emissions due to human activity, resulting in rising global temperatures and changes in the natural environment.

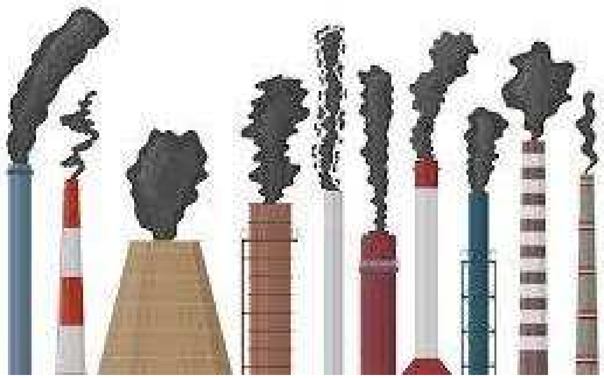




Transitioning from fossil fuels to the era of electricity.

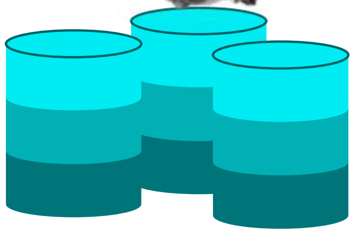
Mitigating CO_2 emissions isn’t just about shifting to electricity and changing fuels.





Maintaining our competitive position demands the adoption of cutting-edge and energy-saving technologies to counter rising energy costs.

Why Microwave need to energy source ?



Microwave : New energy source

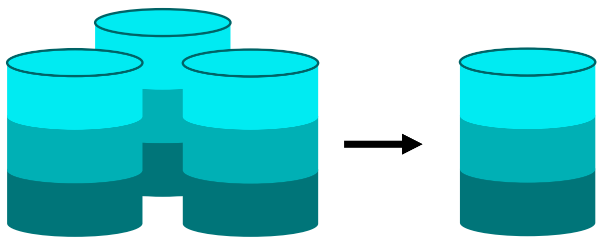
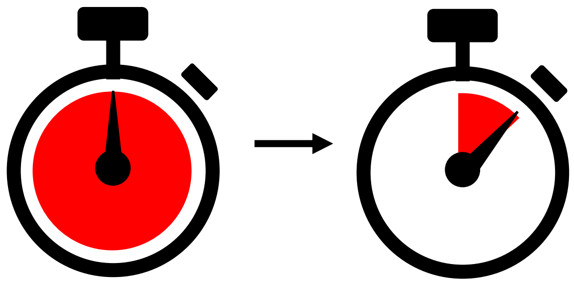
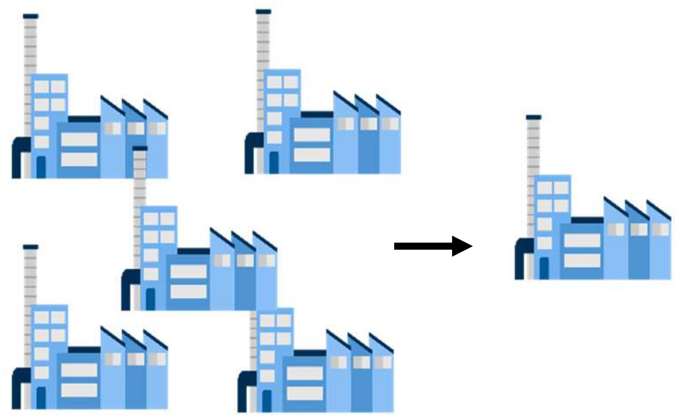
Heating (Over 50% of global energy is used for heating)

Current manufacturing technology using fossil fuels, ect

The utilization of microwave energy sources is a future technology that can significantly enhance the current low energy efficiency.

Benefits of adopting Microwave Technology

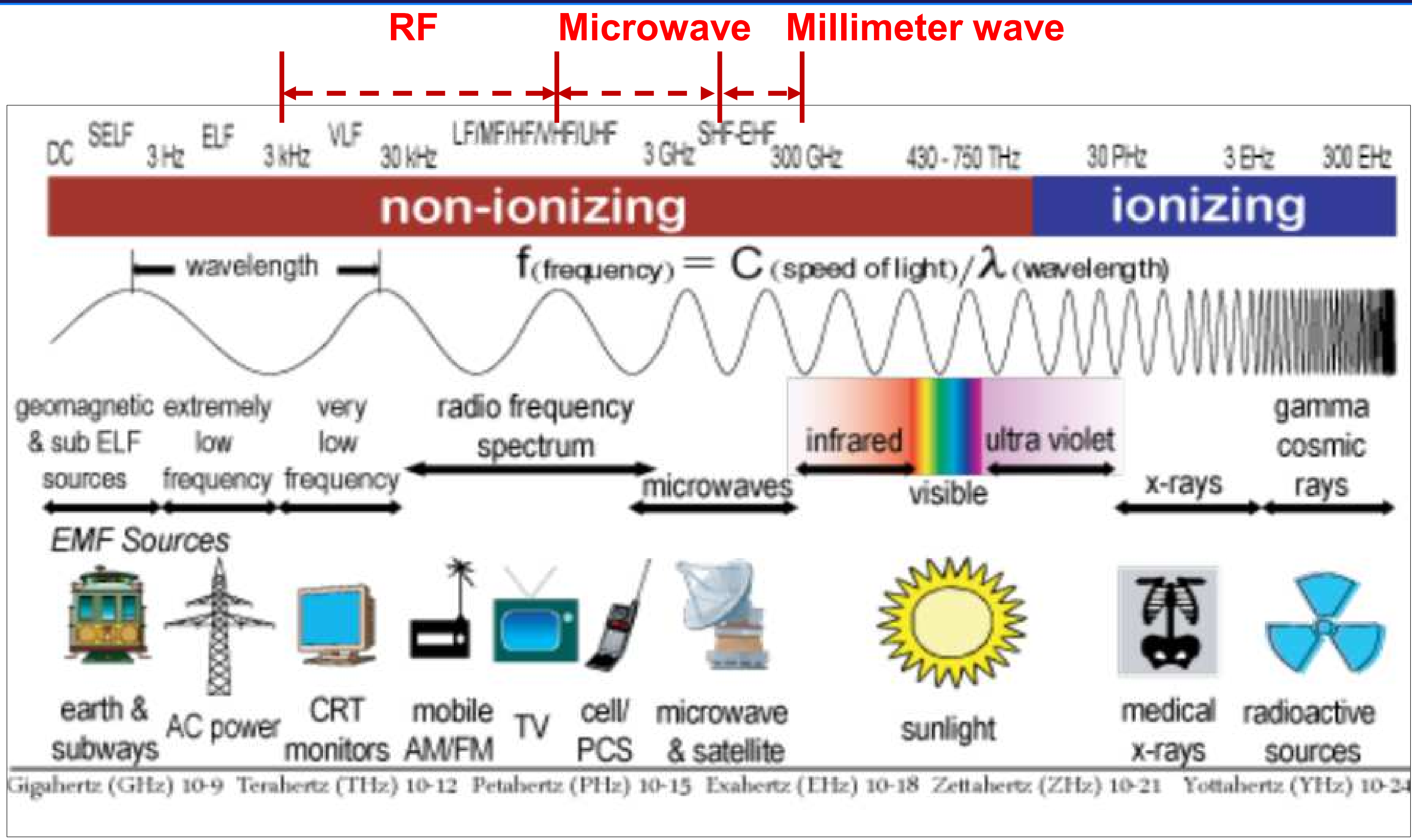
■ **Effects of microwaves on industrial processes**

Saving Energy	Higher efficiency	Compact
Energy consumption ➔ 1/3	Heating time ➔ 1/10	Ground area ➔ 1/5
		
Electricity consumption can be cut to 1/3 of that of conventional methods.	Reactions can be made more efficient than conventional methods.	Single-stage synthesis is now possible, instead of the conventional two stages

3. What is RF energy?

Radio Frequency Introduction

- RF : 3KHz ~ 300MHz 파장 100Km ~ 1m
- Microwave : 300MHz ~ 30GHz 파장 1m ~ 1cm
- Millimeter wave: 30GHz ~ 300GHz 파장 1cm ~ 1mm

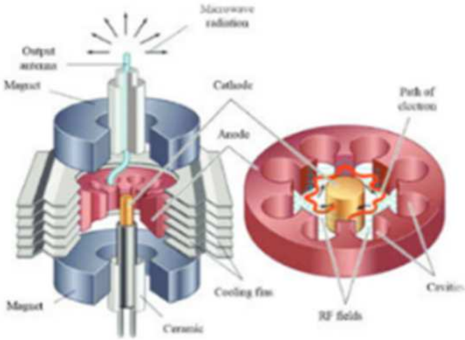


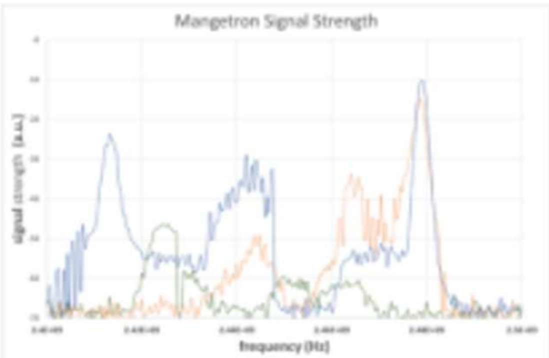
Why Solid-State Generator?

Magnetron M/W Generator

Frequency is not adjustable (Self-Oscillator)

M/W power is adjustable from 10% of Pmax to Pmax



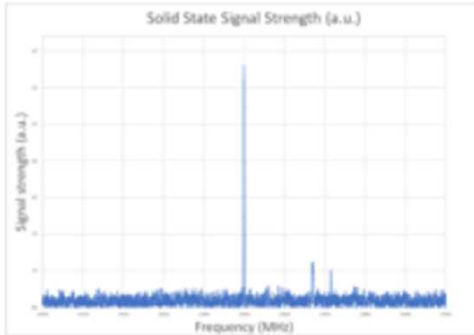


Solid-State M/W Generator

Frequency is adjustable (Amplifier)

M/W power is adjustable 1W to Pmax

Step accuracy 1W



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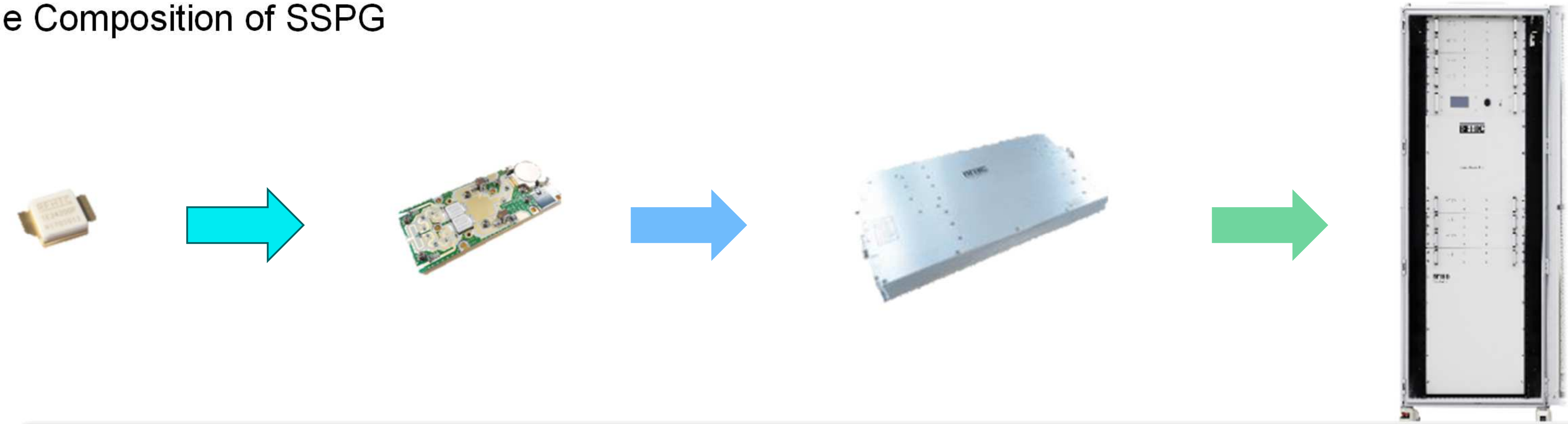
What is Solid-State Generator?

■ The Composition of SSPG



Solid-state Technology

Magnetron vs. SSPA

Item	Magnetron	Solid-state
Configuration	Single	Combining
Power & Frequency Control	Not Capable	Capable (Digitally/Manually)
Lifetime	10k hrs	≥ 100k hrs
Safety	Danger (~15kV)	Safe (~50V)
Harmonics	Very High – 20dBc	Low – 50dBC
Modulation	Not Capable	Pulse, Phase Shift
Power Supply	4~15kV High Cost Loud Operating noise	50V Low Cost Quiet operation
Maintenance Cost (One time)	High OPEX ($10k~)	Low OPEX ($2k~)

Why SSPA?

Digital Controllability
With 1W step

Adjustable
Frequency

10x Longer
Life-time

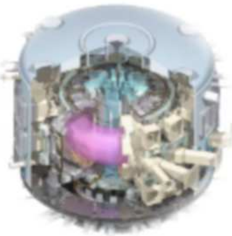
Uniformity
Even heat distribution

Narrow Stable
Spectrum

Compact Size
& Lighter Weight

Where is M/W Generator used ?

Fusion reactor



Secondary battery

Hydrogen synthesis

Accelerator

Semiconductor

Analytical Chemistry

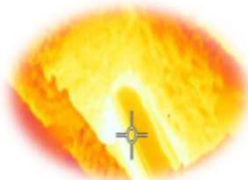
Medical treatment

Plasma Generator

Ablation

Cooking

Material heating



Agriculture

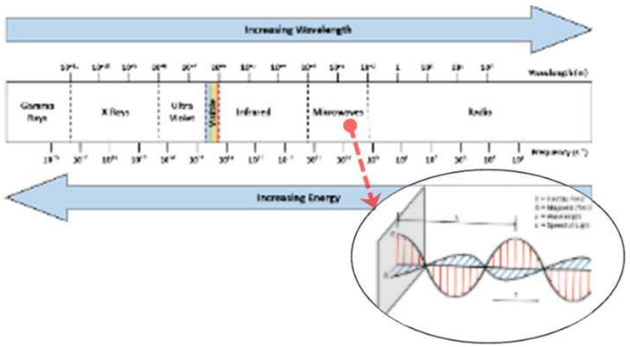
4. M/W Heating for Materials

SSPG Microwave heating system for material.

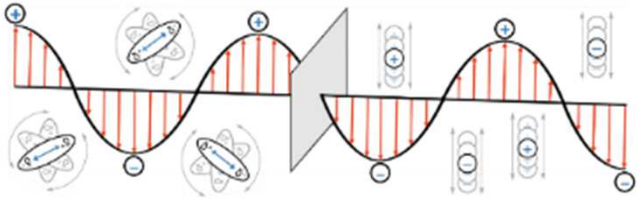
동영상

Advantage of Microwave Processing for Material Heating.

- Microwave



- Mechanisms of Microwave Heating

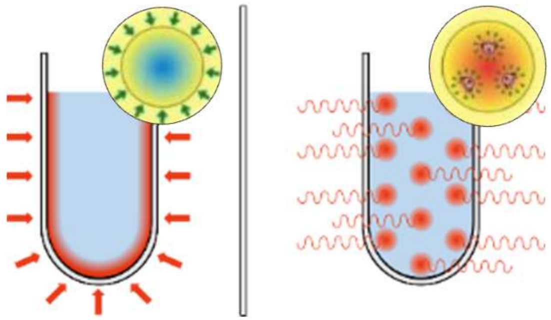


(a) Dipolar Rotatio
n

(b) Ionic Condu
ction

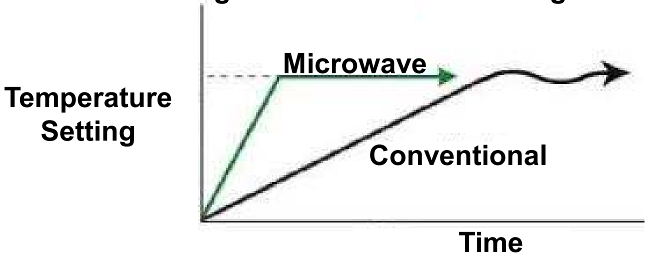
Ref : CEM – Microwave Heating

- Compare of Heating Mechanism

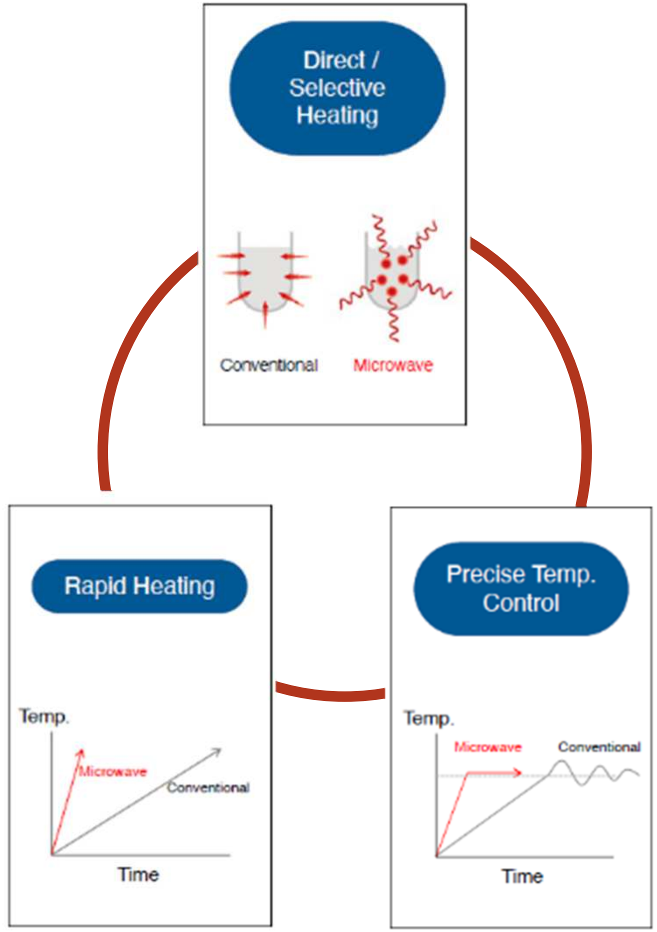


(a) Conductive He
ating

(b) Microwave Heati
ng

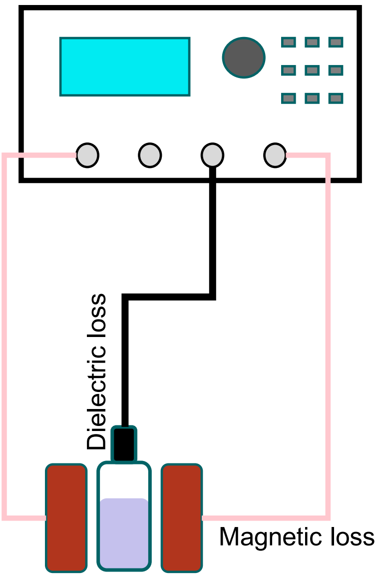


Ref : Micro Denshi CO.ltd – Basic Knowledge of microwave heating

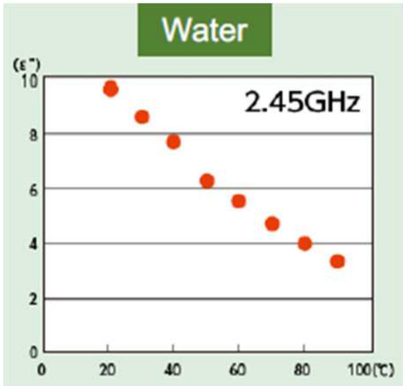


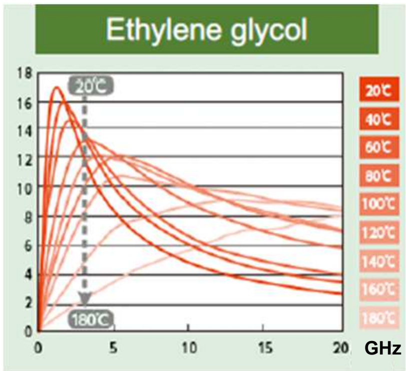
Reasons for Measuring Dielectric Constant for M/W Heating

소재 마다 마이크로웨이브 흡수율은 소재별 복소 유전상수값의 차이에 의해 상이함.
이러한 이유로, 마이크로웨이브 가열 실험이전 복소 유전상수 측정이 선행되어야 함.



Microwave absorption





[Measurement of microwave absorption ability of each component]

Loss Classifications	Material category	Calculation formula
Conduction loss (전도성 가열)	Carbon material, Ionic liquid	$\frac{1}{2}\sigma\lvert E\rvert^2$
Dielectric loss (유전체 가열)	BaTiO3, H2O, Alcohols	$\pi f \varepsilon_0 \varepsilon_1'' \lvert E\rvert^2$
Magnetic loss (자성가열)	Ni, Co, Fe3O4	$\pi f \mu_0 \mu_r'' \lvert H\rvert^2$

Conduction loss (전도성 가열) / Dielectric loss (유전체 가열) / Magnetic loss (자기 가열)

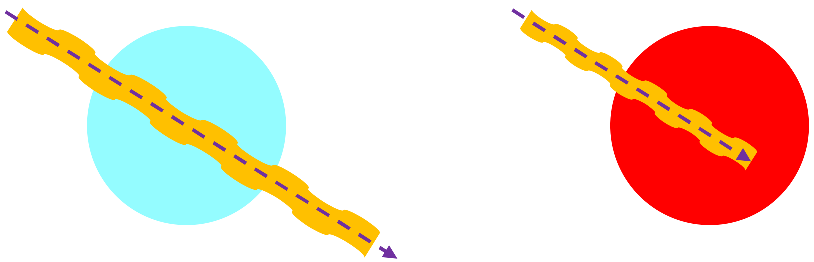
$$P_{total} = \frac{1}{2}\sigma\lvert E\rvert^2 + \pi f \varepsilon_0 \varepsilon_1'' \lvert E\rvert^2 + \pi f \mu_0 \mu_r'' \lvert H\rvert^2$$

$$P = \varepsilon'' \cdot E2$$

ε'' = A material-specific value called the dielectric loss factor. (유전손실 계수의 재료별 값)
ε_1'' = 물질에 따른 마이크로웨이브 흡수율 / 복소 유전율 상수
ε_0 = 자유공간의 유전율
P_{total}= 단위 부피당 마이크로웨이브 가열 속도 Ptotal(W/m3)
σ = 자유공간의 진공율 (8.854 x 10^{-12} F/m)
$\lvert E\rvert$ = 전기장의 벡터 (E)의 크기
$\lvert H\rvert$ = 자기장 벡터(H)의 크기
μ_0 = 자유공간의 투자율
μ_r'' = 유전체의 투자율 / 복소 투자율
E = The strength of the electric field (V/m) produced by the microwave, that acts on the material.

The principle of selective heating of substances using microwaves.

Substance with small ε'' < Substance with large ε''



◎ 물질의 유전상수 값이 작은 경우

-. M/W 물질 통과 (흡수 되지 않음)

-. M/W 가열이 일어나지 않음

◎ 물질의 유전상수 값이 클 경우

-. M/W 물질 통과되지 않음 (흡수됨)

-. M/W 가열 발생됨

[유전 상수값과 마이크로웨이브의 가열 용량 사이의 관계]

$$P_{total} = P_{\varepsilon} + P_{\sigma} + P_{\mu} = \frac{1}{2}\omega\varepsilon_0\varepsilon'' E^2 + \frac{1}{2}\sigma E^2 + \frac{1}{2}\omega\mu_0\mu'' H^2$$

[재료의 단위 부피당 마이크로파 가열 속도]

E : Electric fild, H : *Magnetic fild*, ω : *Frequency*

E_0, μ_0: *Permittivity*, σ : *Conductivity*

ε'': *Complex pemittivity*, σ : *Conductivity*

μ'' : *Complex magnetic permeability*

P_{total}: 단위 부피당 마이크로웨이브 전체 가열 속도 Ptotal(W/m³)

P_{ε} : 유전체 물질 가열 속도 (W/m³)

P_{σ} : 전도성 물질 가열 속도 (W/m³)

P_{μ} : 자성 물질 가열 가열 (W/m³)

General parallel plate capacitance measurement method

■ **일반적인 평행판 캐패시터의 전기용량 측정 공식 : LCR 계측기 없을 경우**

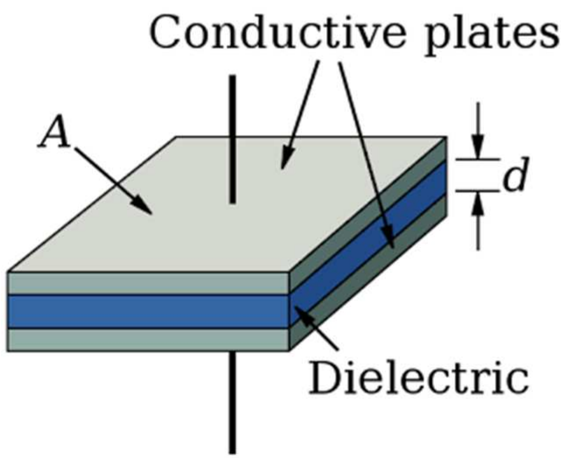
$$C = \frac{1}{\int_A^B \frac{dl}{\int_\delta \varepsilon\, da}} = \varepsilon \frac{1}{\int_A^B \frac{dz}{\int_\delta dxdy}} = \frac{\varepsilon A}{d}$$

위 식에서 물리적 크기(A, d)에 의해 전기 용량 (permittivity) ε이 정해 짐.

$$\bar{P} = \varepsilon_0 X_e \bar{E}$$

$$\rightarrow \bar{D} = \varepsilon_0(1 + X_\varepsilon)\bar{E} = \varepsilon_0\varepsilon_r\bar{E} = \varepsilon\bar{E}$$

유전 상수와 유전율은 위 식의 관계를 가지므로 유전 상수 ε_r이 결정됨.
(물리적 크기가 고정되면 유전 상수가 커질수록 전기 용량이 커짐.)



[캐패스터 구조 개략도]

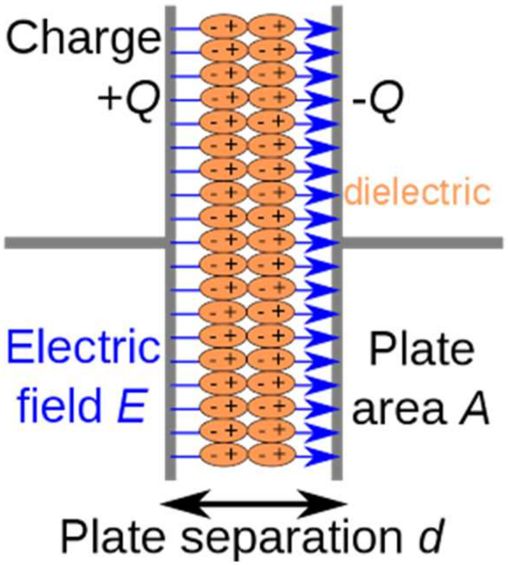
Note : LCR 계측기가 없다면 캐패시턴스 충전과 방전 실험을 통해 오차 편차가 크지만, 값싼 방법으로 전기 용량을 상기 내용으로 계산을 할 수 있음.

Capacitive dielectric constant measurement method

■ **LCR 계측기 측정 방법 :**

-. LCR 계측기를 이용해 Capacitance의 전기용량을 실험적으로 정확하게 측정 가능함.

-. 하지만, LCR 계측기 소자의 저주파 특성으로 주로 kHz ~ MHz 주파수 영역만 측정이 가능함.
GHz를 넘는 고주파 영역은 LCR 계측기로 측정 할 수 없음.



[캐패스터 구조 개략도]

[LCR 계측기_Keysight / E4980A]

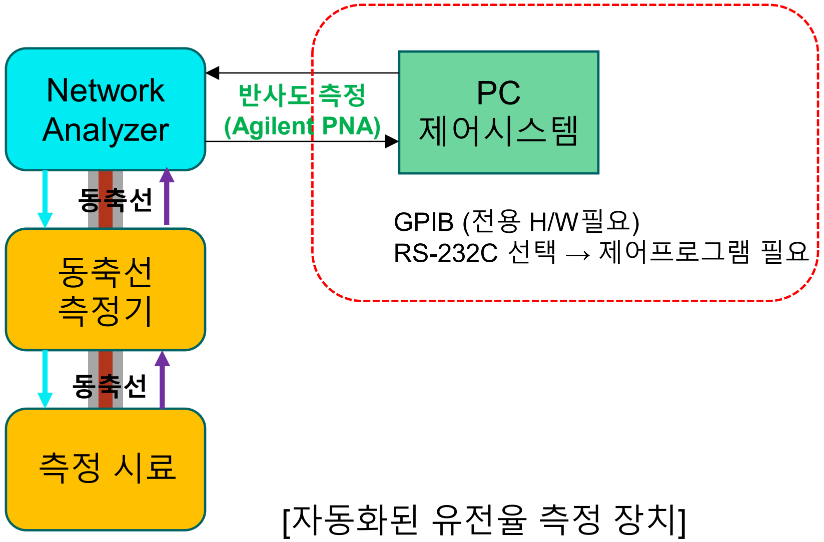
Capacitive dielectric constant measurement method

■ **반사도 계수 방법 (Reflection Coefficient Method) :**

※ '회로망 분석기'의 장점 :

1. 회로망 분석기를 사용하면 굉장히 정밀한 유전 상수측정이 가능함.
2. 회로망 분석기는 LCR 계측기와 다르게 GHz까지도 측정이 가능함. (고주파 측정이 가능한 장비임)
3. 소재의 유전율 측정은 번거로운 과정이므로, 자동화된 측정법 필요.
4. 요즘 나오는 회로망 분석기는 자동화 측정을 지원하는, GPIB(General Purpose Interface Bus) 혹은, 네트워크 카드가 필수 장착되어 있음.

[회로망 분석기 / Network analyzer]



[자동화된 유전율 측정 장치]

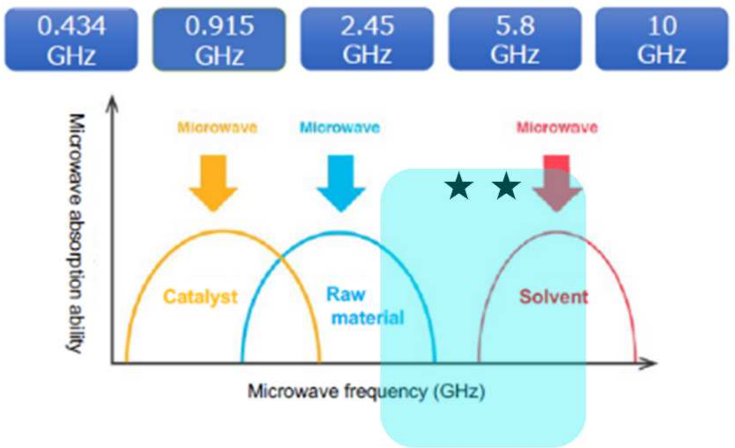
Measurement Method for Dielectric Constant of Materials

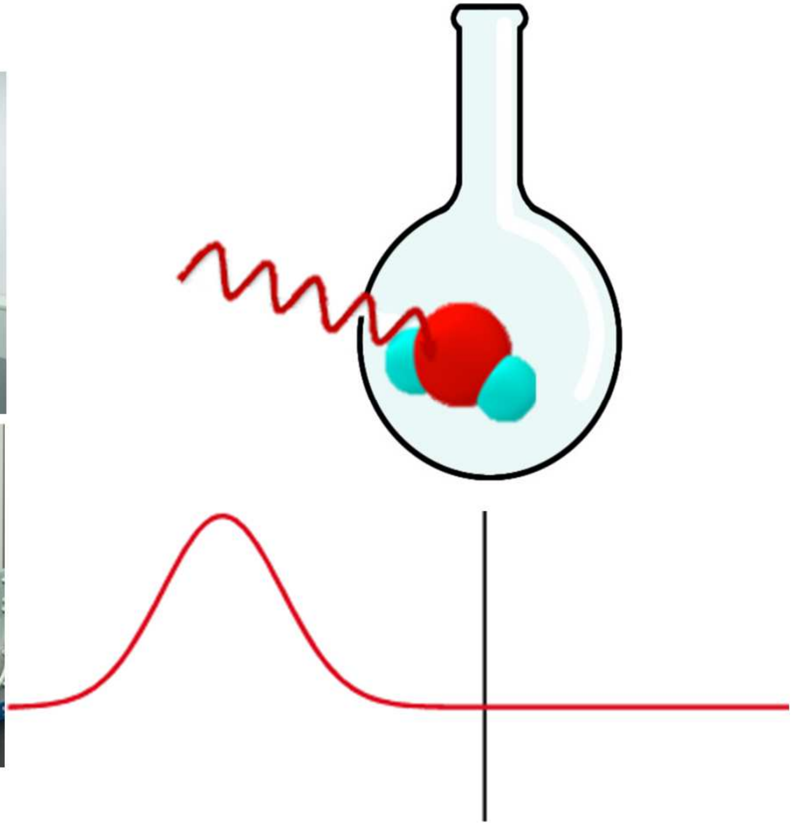
■ **반사도 계수 방법 (Reflection Coefficient Method) :**

-. 반사도가 측정되면 식 아래의 식에 의해 부하 임피던스(load impedance)를 알 수 있음.

-. 부하의 유전율을 바꾸면 부하 임피던스가 바뀐다.

$$\Gamma_L = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

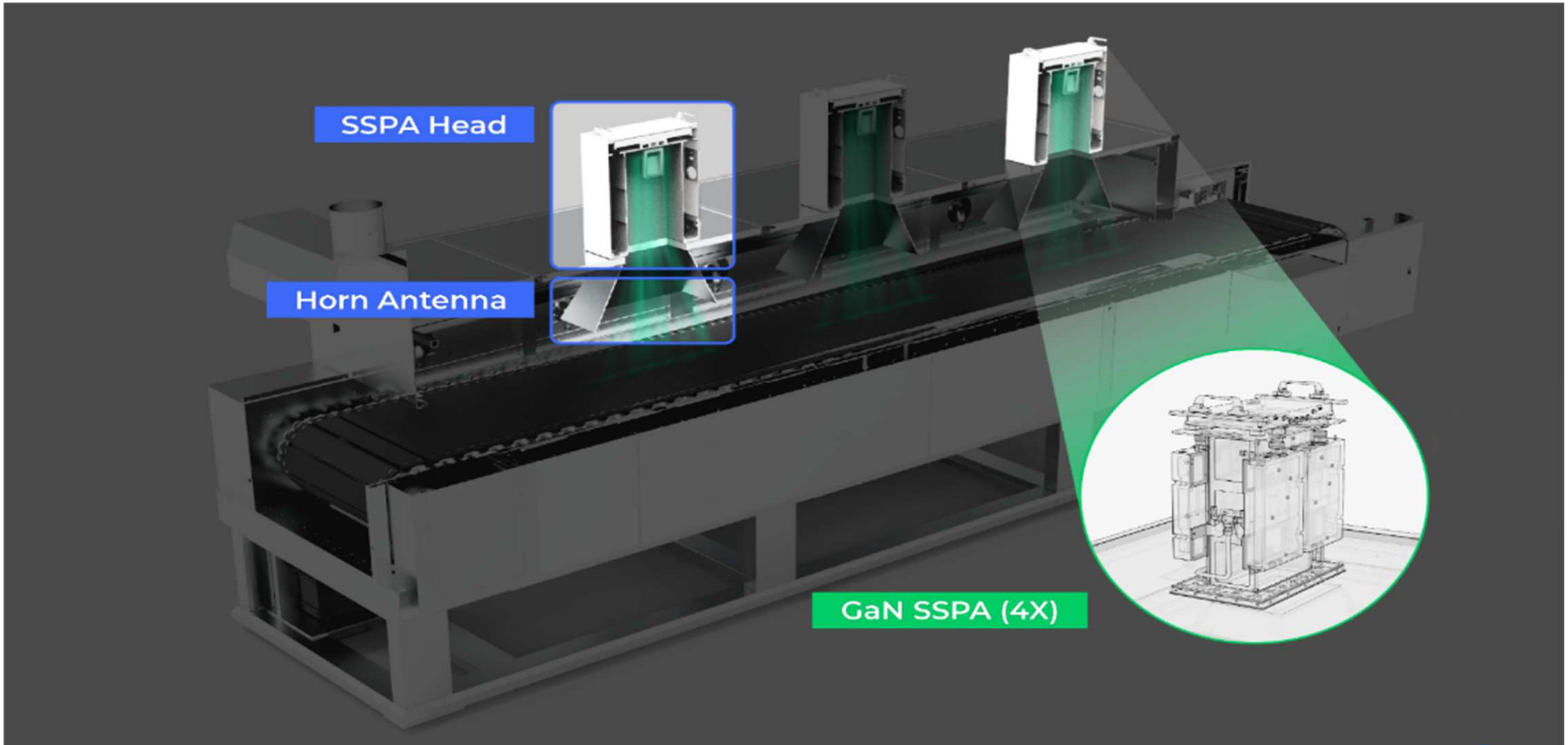




[Microwave Absorption]

-. 마이크로파 흡수는 각 물질마다 고유하며 온도와 주파수에 따라 흡수율이 달라짐.

[Application case] GaN SSPG M/W Heating for Conveyor Systems



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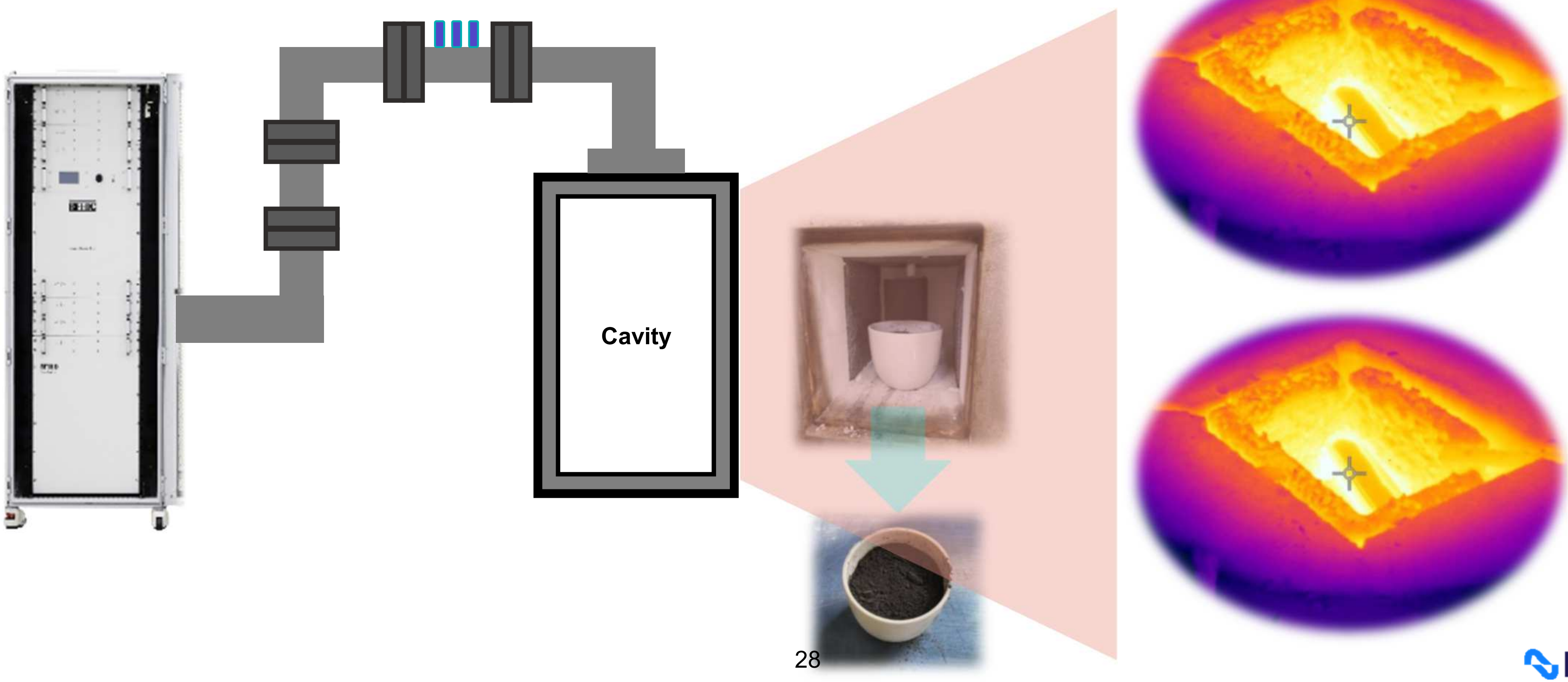
[Application Case] GaN SSPG M/W Heating for anode material

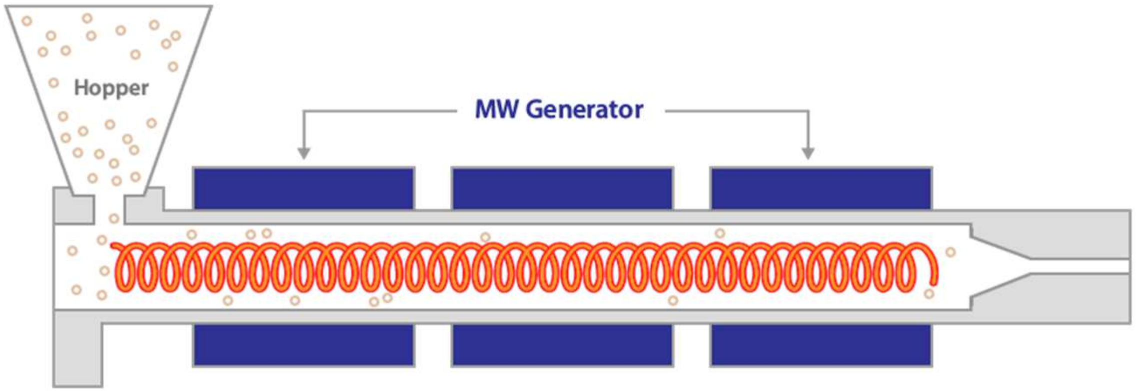
Microwave Heating for Li-battery cathode

M/W Heating System



[Application Case] GaN SSPA Heating for Foaming Systems

Microwave Foaming Systems



The expansion of foam during MW processing can be controlled using our GaN SSPA technology

Uniform cellular structure	Conductivity
Low density	Mechanical and thermal stability

Characteristics of MW Assisted Foams

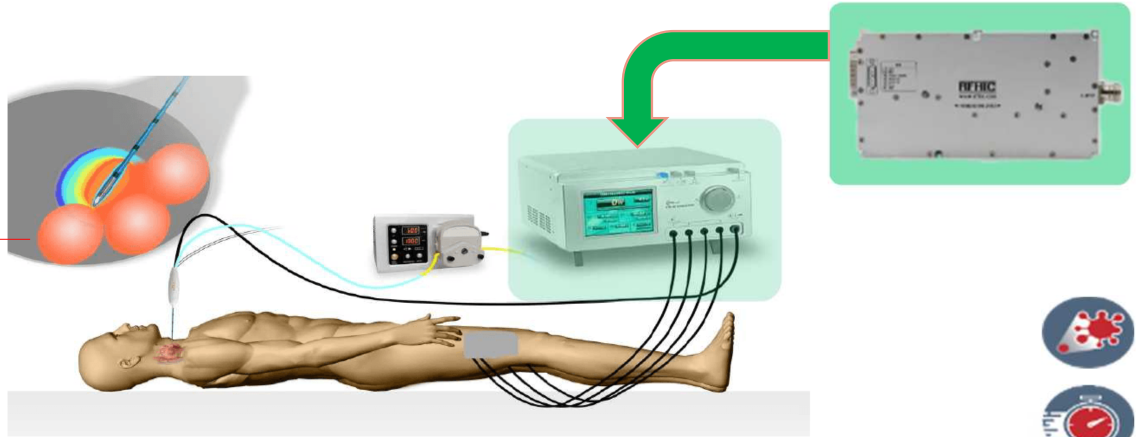
Uneven foam density

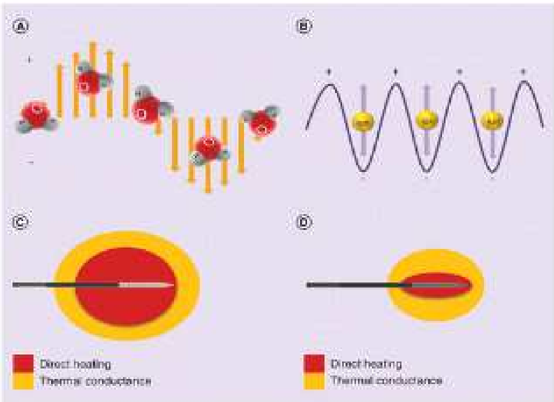
Uniform foam density

RFHIC

[Application Case] GaN SSPA M/W Heating for Ablation

Microwave Ablation





Difference in Tumor Convection Profile between the two different types of ablation methods.

Applications :

- Microwave Ablation (Tumor, Liver, Cardiac)
- Microwave Medical Aesthetic device
- Microwave Diathermy

Larger Tumor Ablation Volumes

Faster Ablation Times

Consistent and Higher Intertumoral Temperatures

Benefits of Microwave Technology for Tumor Ablation Applications :

- **Larger** & **Faster** Ablation Zones
- RFHIC's **Phase Control Capabilities** → Precise Ablation Control Capability
- Capable of penetrating through various tissues, even those with high impedance (ex. Lung, Bone)
- Uniform Heating
- Less susceptibility to Heat-sink Effect
- Generate higher temperature vs. RF
- **Improved Convection** Profile of Tumor

[Application Case] GaN SSPA M/W Heating for Diathermy

Microwave Diathermy

RIP25028-20G

Output Power	26W
Frequency	2,400~2,500MHz
Efficiency	60%

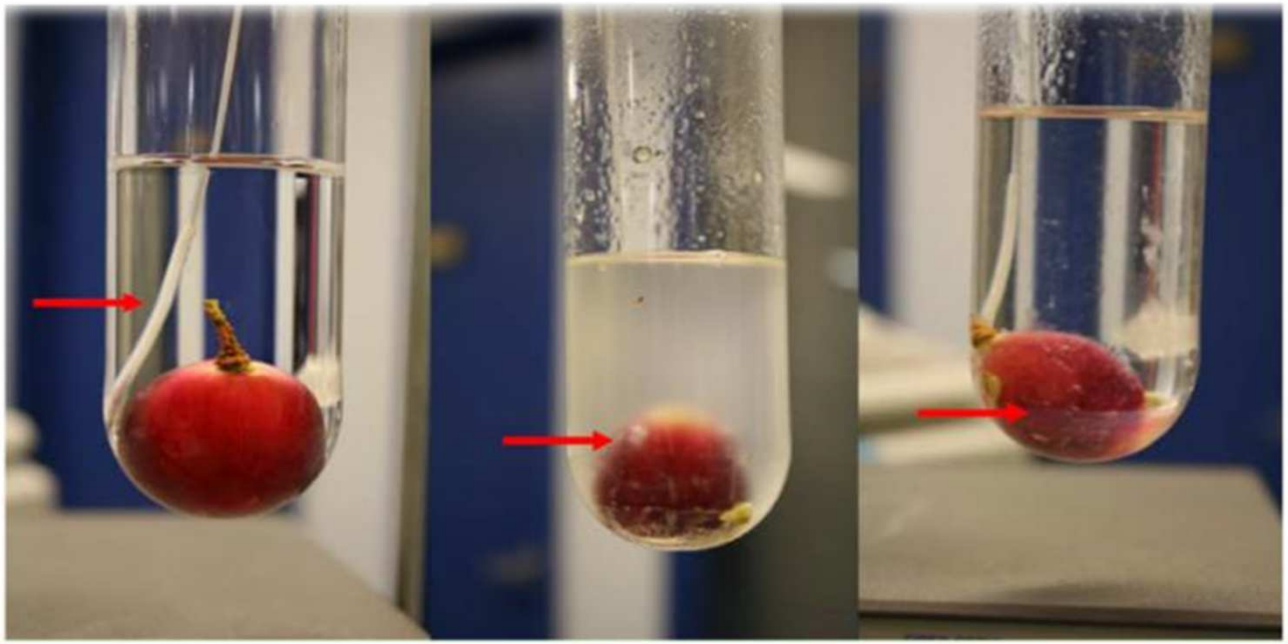
Uniform and Consistent Heating Distribution

Faster Heating Times

Excellent Directivity For Precise Radiation

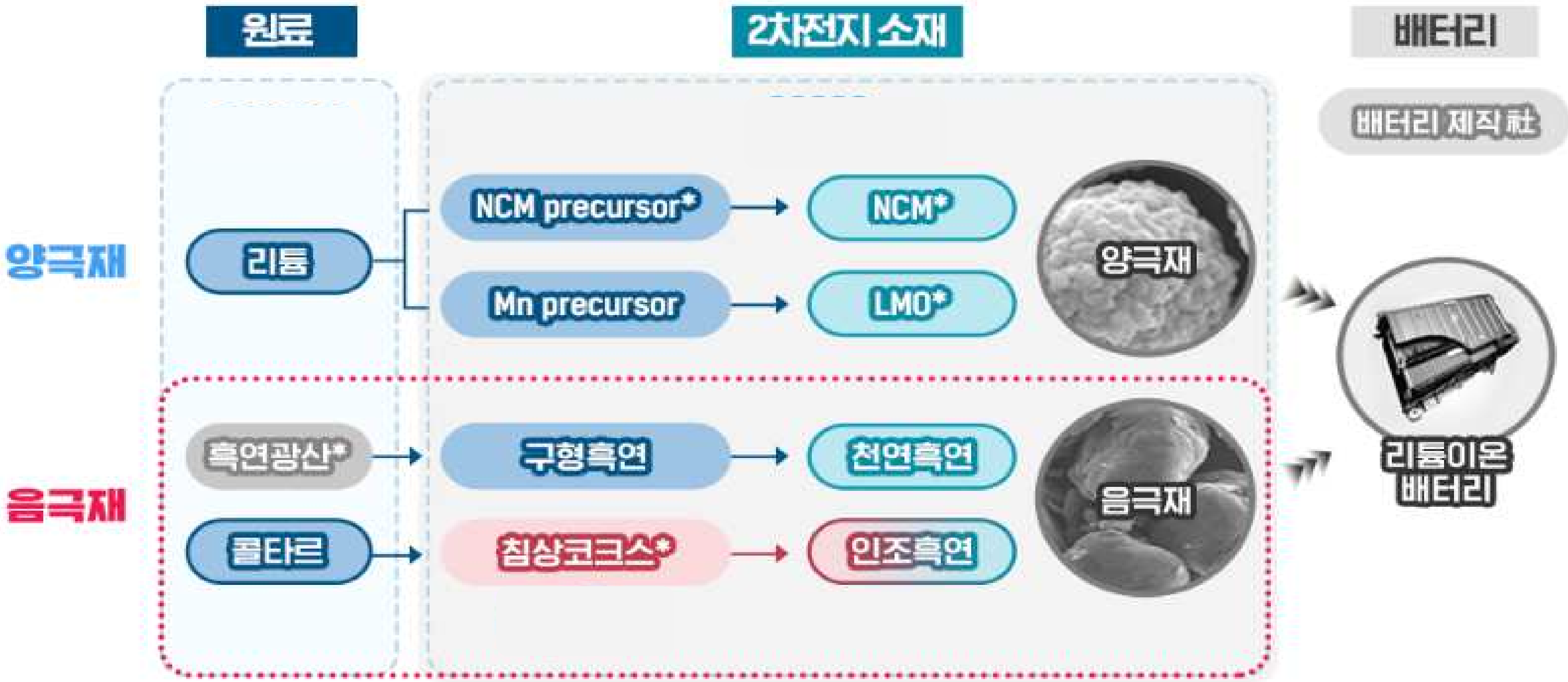
- Adjustable Frequency & Power Capabilities
- Excellent Power Efficiency
- Custom Solutions Available
- Compact & Portable System

[Case study] Extraction from food(grape) with hexane



Conditions: grape extraction was done in hexane. Irradiation time was 30 sec and the power 240 W.

[Case study] Anode-cathode active material M/W drying process



[자료 출처 : POSCO]

As-is : Drying process length 30~ 40m

The length of the drying process can be reduced to 1/10 level by using microwave.

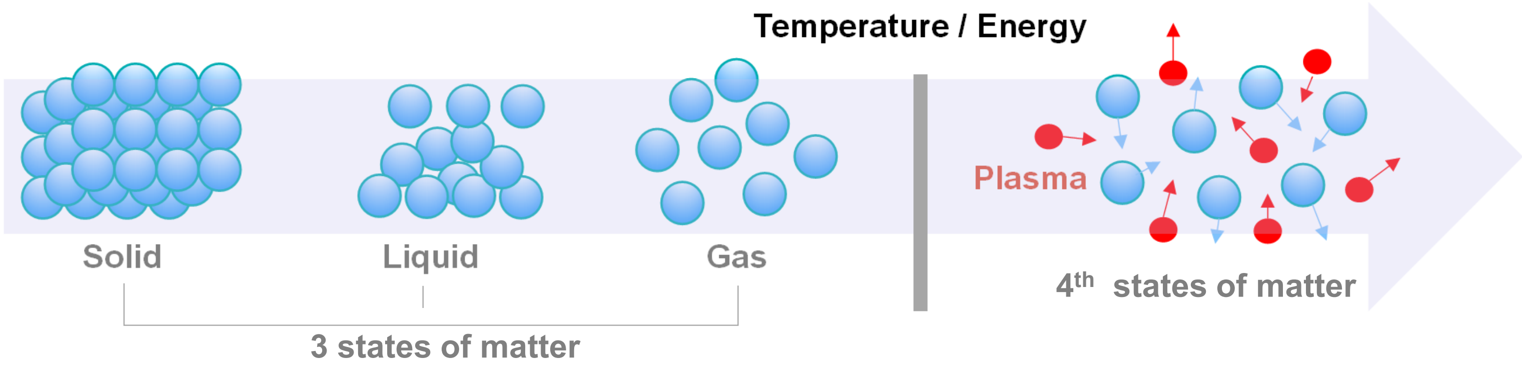
[Case study] Asphalt pothole treatment using microwave heating.

http://www.mnltap.umn.edu/publications/exchange/2013/fall/microwaves.html

5. M/W Heating for Plasma applications

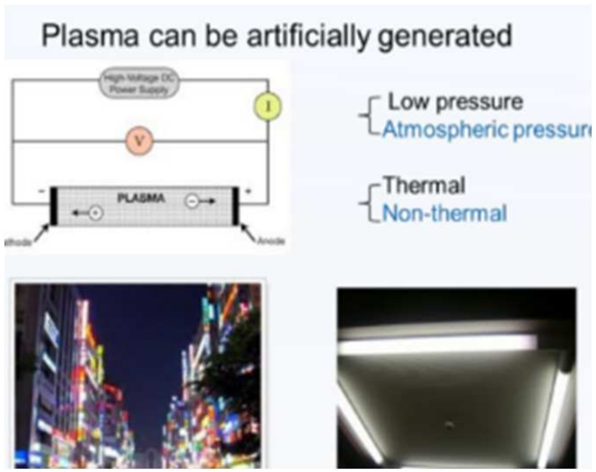
Introduction of Plasma

Plasma, the fourth state of matter,' is a collection of charged particles (electrons, ions, neutral atoms), various active species, and UV photons.

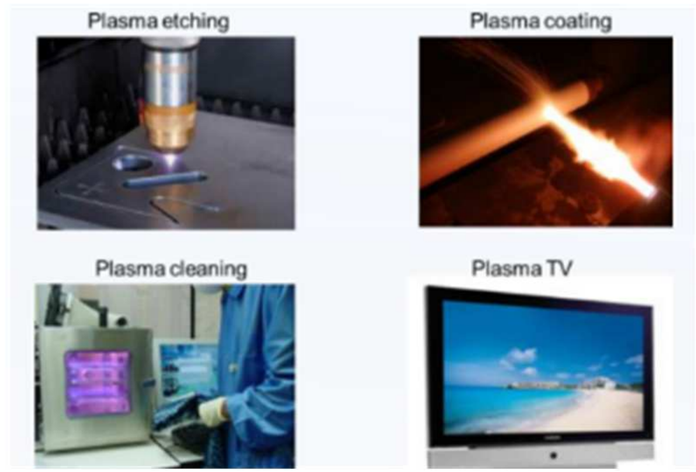


Plasma in nature

Artificial plasma

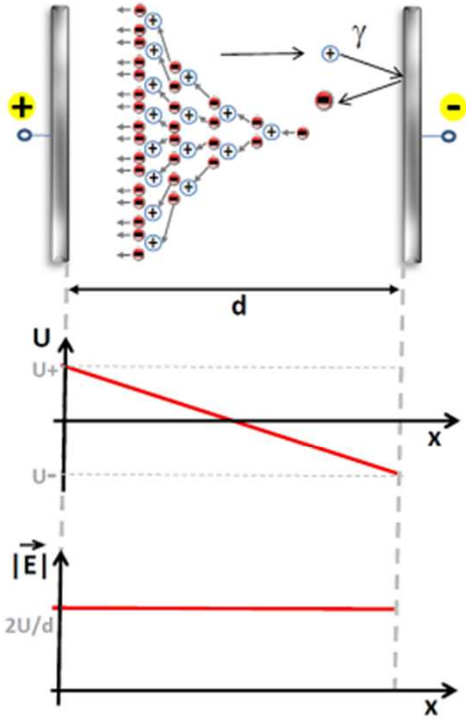


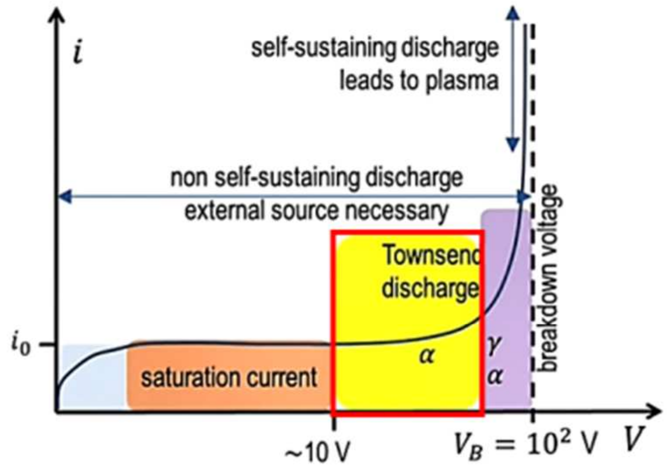
Industrial application of plasma



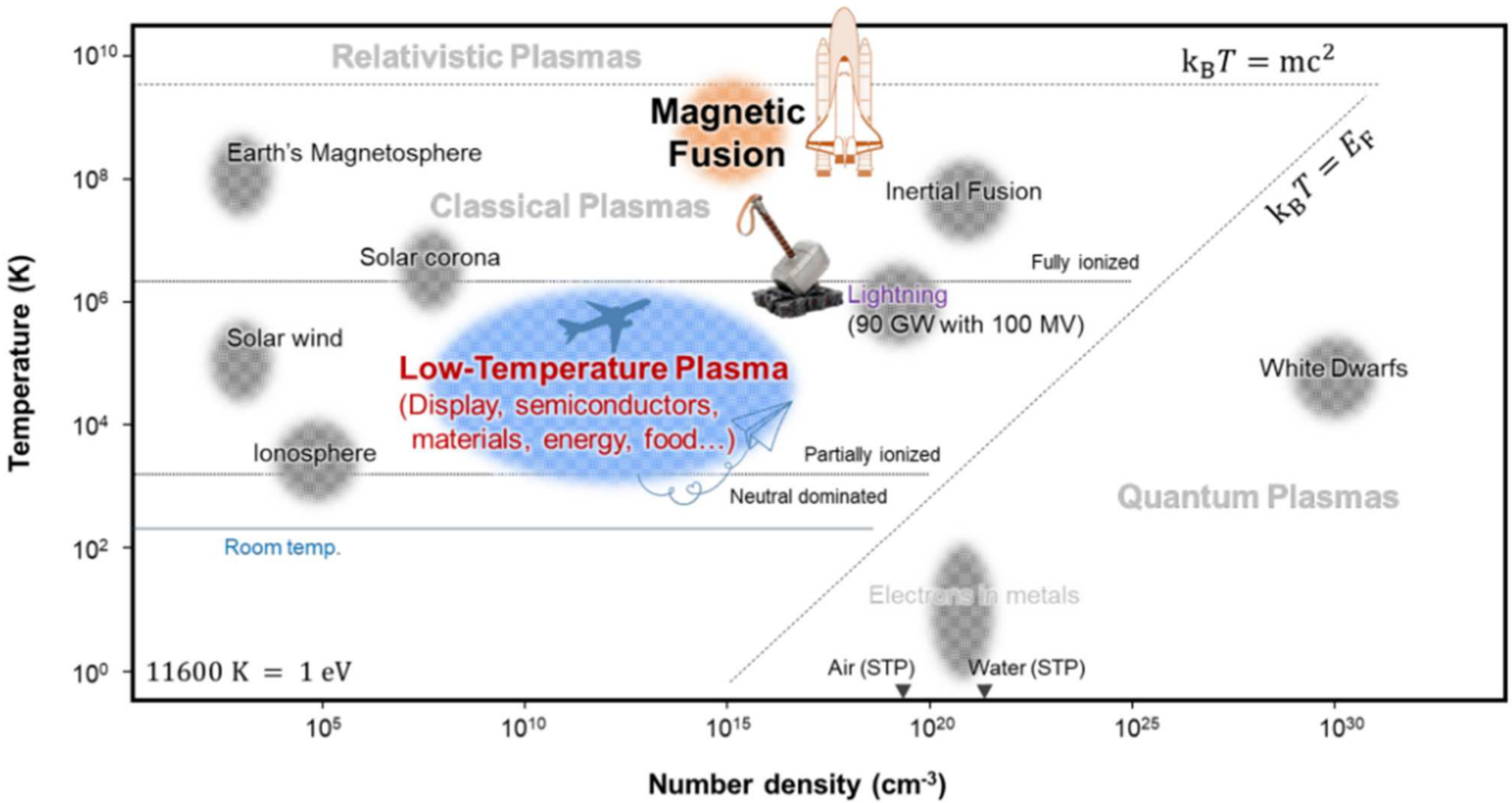
Plasma generation

- Breakdown mechanisms
  - Townsend avalanche





Plasma classification and characterization



Plasma Type

	Thermal Plasma	Cold Plasma
Generation	Arc discharge	Glow or Corona discharge
Power supply	DC, AC, RF (SSPA) (Low voltage, High current)	DC, AC, MW(magnetron), RF (High voltage, Low current)
Temperature	$\boldsymbol{T_e = T_i = T_g = 10^3 - 10^5\mathrm{K}}$ LTE High thermal capacity	$T_e = 10^4 - 10^5 K, T_i = T_g = few10^3 K$ Non-LTE Low thermal capacity
Plasma Density	$\boldsymbol{10^{15} \sim 10^{19} cm^{-3}}$	$10^8 \sim 10^{13}\ cm^{-3}$
Pressure	$\boldsymbol{10 \sim 10^3\ torr}$	$10^{-4} \sim 10^3\ torr$ (glow discharge) $10 \sim 10^3\ torr$ (corona discharge)
Uniformity	Medium or Poor	High (glow) Low (corona)
Major Role	High-temperature heat source	Physical & Chemical reactor

Plasma classification

Artificial Plasma

Plasma pyrolysis for H2

High temperature Plasma (Fully ionized)

Equilibrium plasma (Thermal plasma)
Te ~ Tgas >> Troom

RFHIC's Plasma Torch

N

m

RF ICP　Microwave　Thermal Arc

Case Studies : CVD reactor & Plasma torch

CVD Reactor

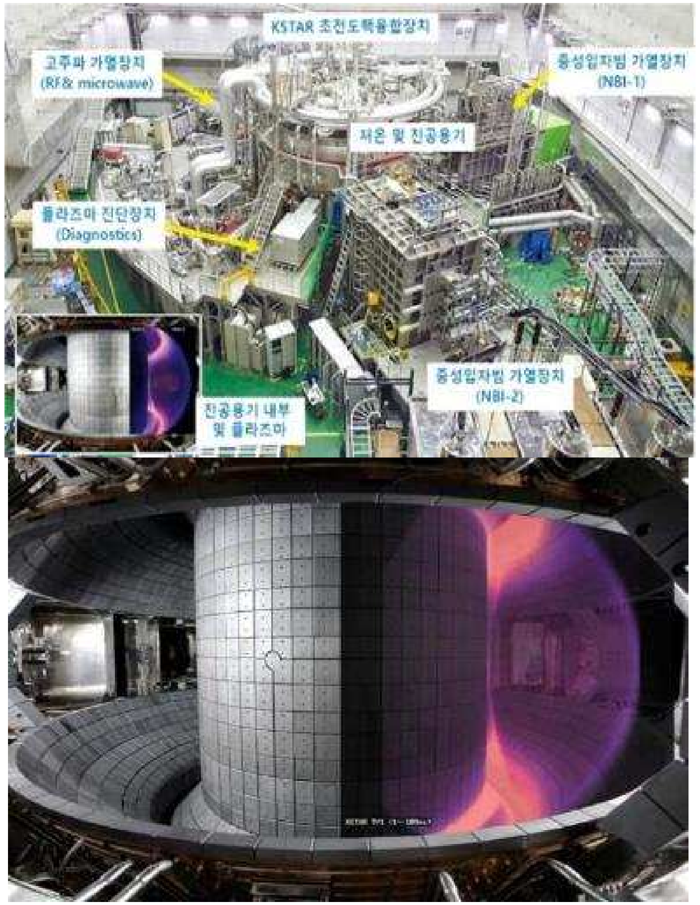
RFHIC Corporation Plasma Chamber for CVD

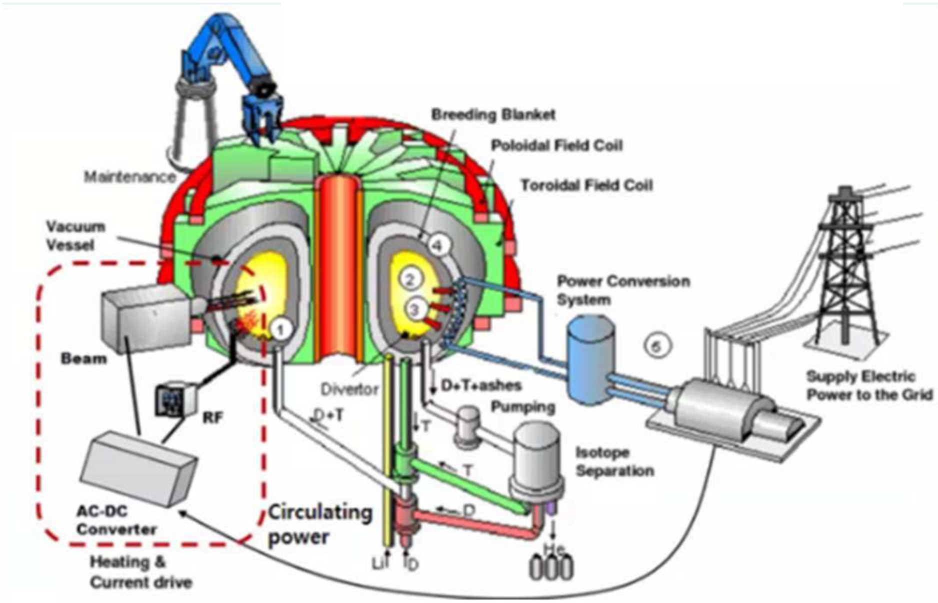
Plasma Torch

RFHIC Corporation Plasma Torch Application

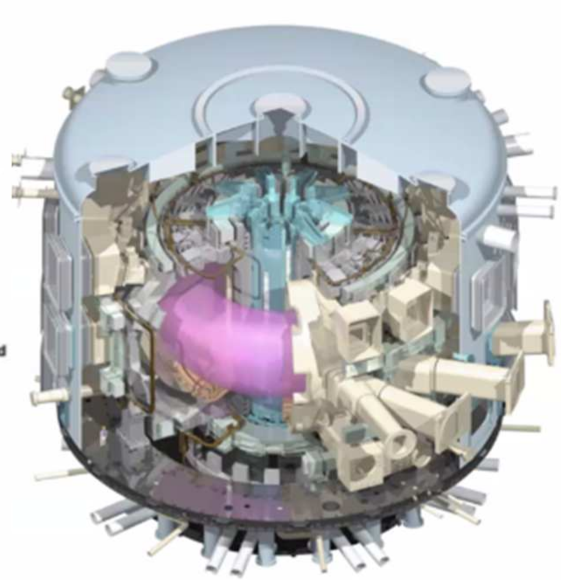
Case Study : Plasma heating of fusion reactor

K- Star & Tokamak



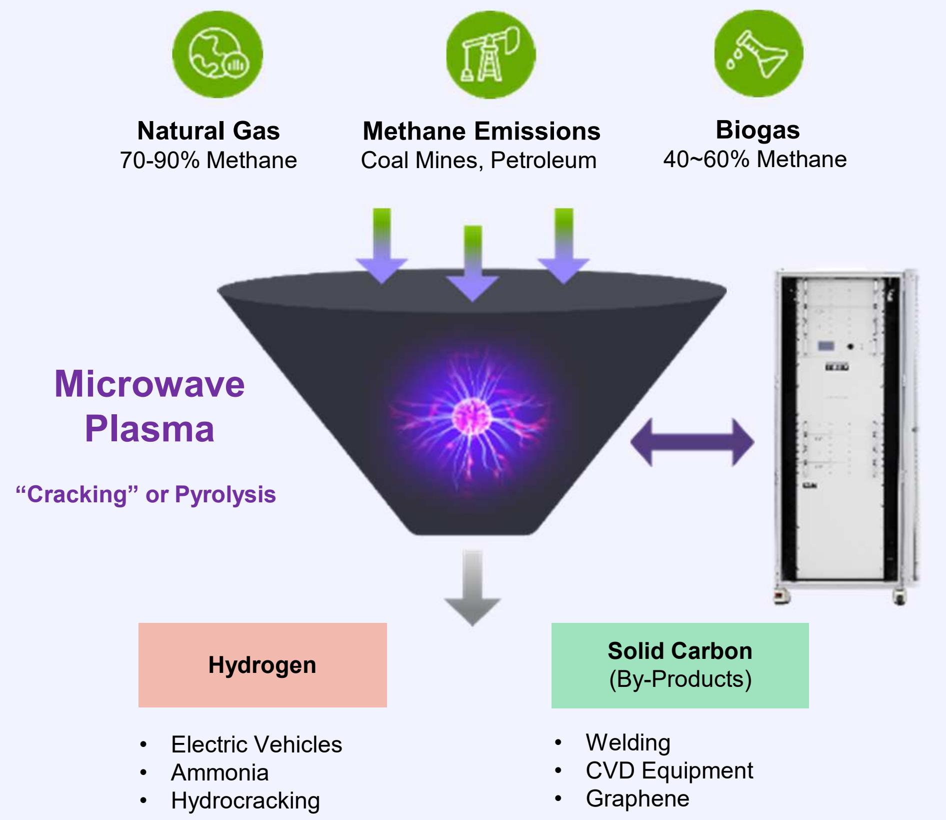


ITER Tokamak



[사진 출처 : 한국핵융합에너지연구원]

Case Study : Plasma Conversion Technology



Sources: TM, R, BASF, SC

• Key Advantages

Zero Water & GHGs

No water consumption and zero CO_2 process emissions

4x Less Energy Consumption

Electricity vs. Competing Hydrogen Technologies
(Source: TM)

Economic Advantages

Produce other solid carbon by-products for profitable use.
Ex) Acetylene, Graphene, Ammonia

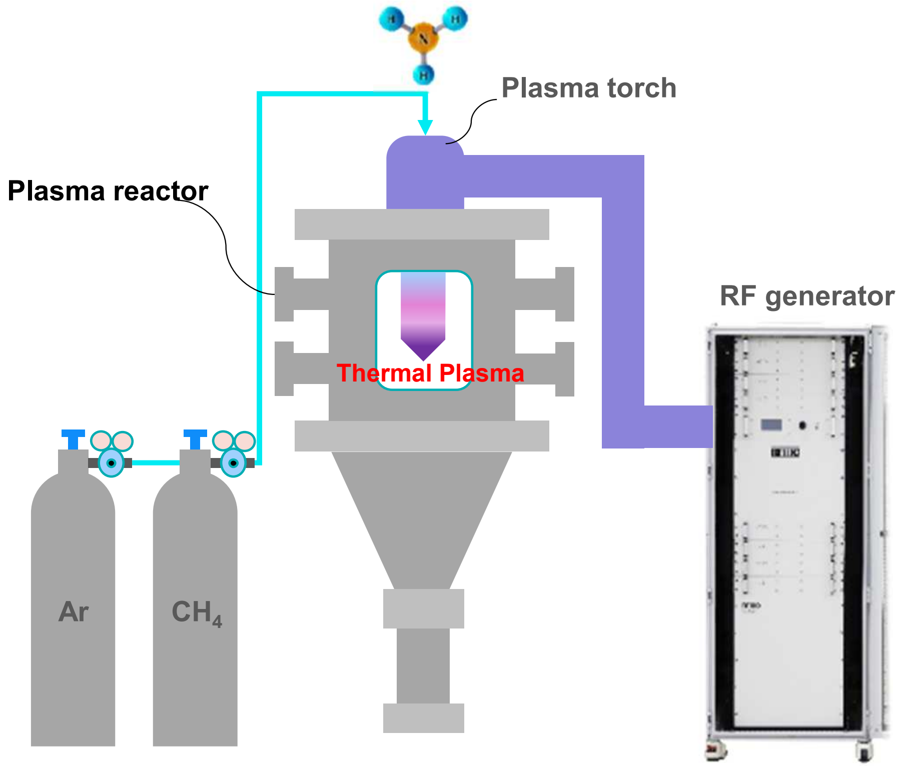
Efficient & Stable

Microwave plasma using GaN solid state provides a highly efficient and stable source of plasma offering higher scalability for commercial production

Case Study : M/W Plasma pyrolysis for hydrogen production

Hydrogen production method	Reaction formula	Energy requirement (kWh/kg H_2)	$\frac{mol\ CO_2}{mol\ H_2}$	$\frac{mol\ C}{mol\ H_2}$	$\frac{mol\ C}{mol\ H_2}$
Methane pyrolysis (Plasma pyrolysis)	$CH_4 \leftrightarrow C = 2H_2$	16.28	-	0.5	
Dry reforming	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	24.50	0.34	0.54	0.47
Steam reforming	$CH_4 + 2H_2O \leftrightarrow 4H_2\_CO_2$	10.84	0.32	0.32	1.00
Partial oxidation (POX)	$3CH_4 + 2O_2 + 2H_2O \leftrightarrow 4H_4 + 3CO_2$	-	4.48	4.48	1.00
Coal gasification	$2C + 4H_2O + CO_2 \leftrightarrow 4H_2 + 3CO_2$	3.76	0.77	0.77	1.00
Electrolysis	$H_2O \leftrightarrow H_2 + 0.5O_2$	47.99	-	-	-
Auto-Thermal reforming	$3CH_4 + 2O_2 + 2H_2O \leftrightarrow 8H_2 + 3CO_2$	5.76	0.31	0.31	1.00

Schematic of plasma pyrolysis system

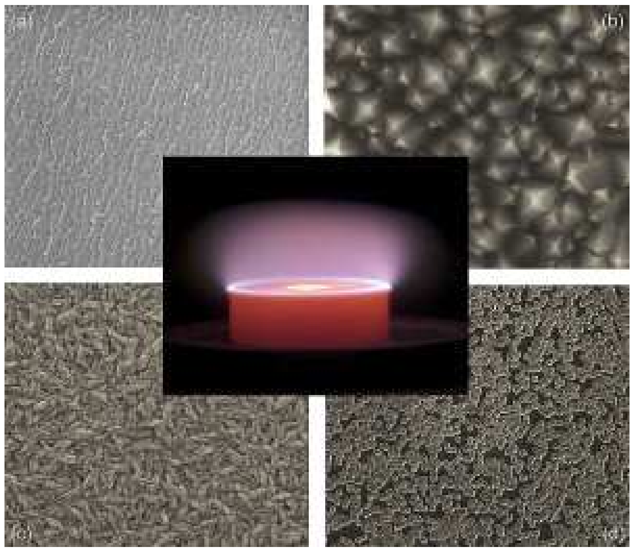


RFHIC

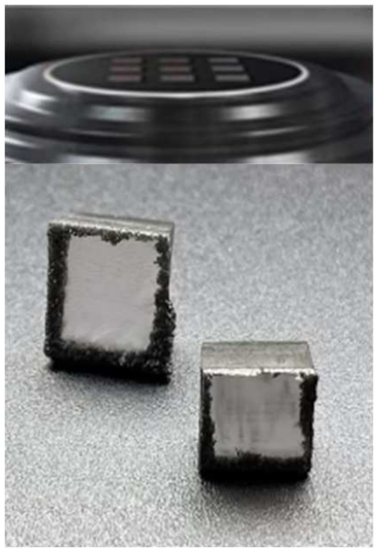
Case Study : MP-CVD for artificial diamond

MP-CVD 장비

M/W Plasma



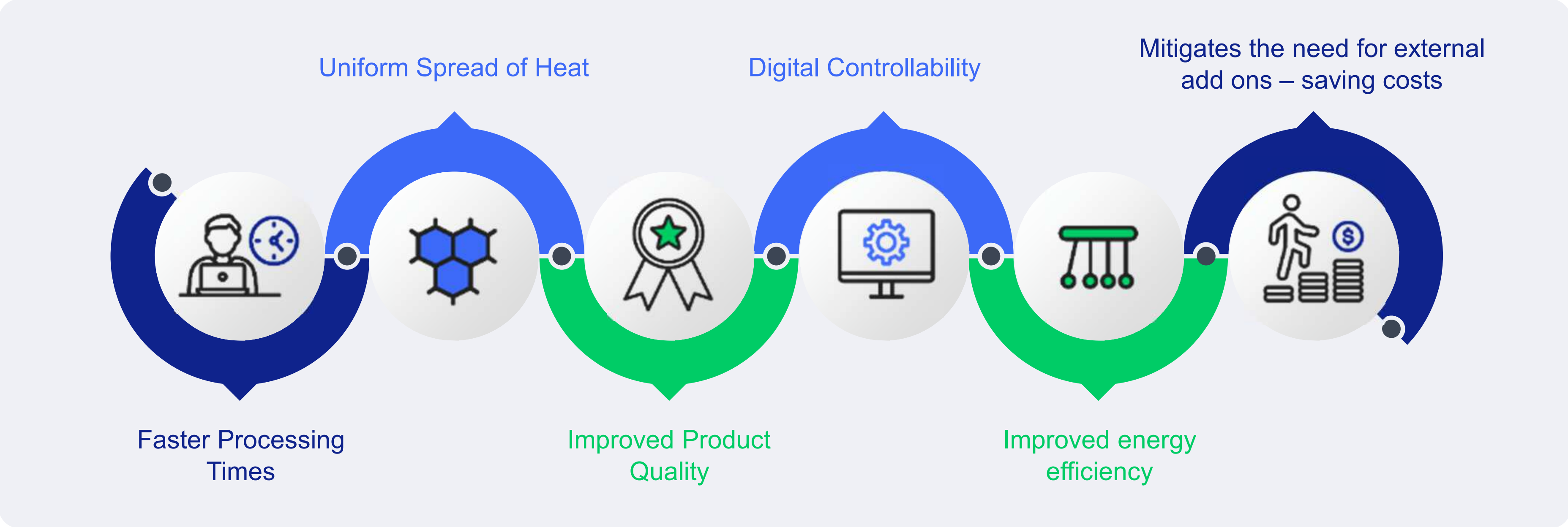
Artificial Diamond



6. Summary

Summary : Benefits of RF Energy

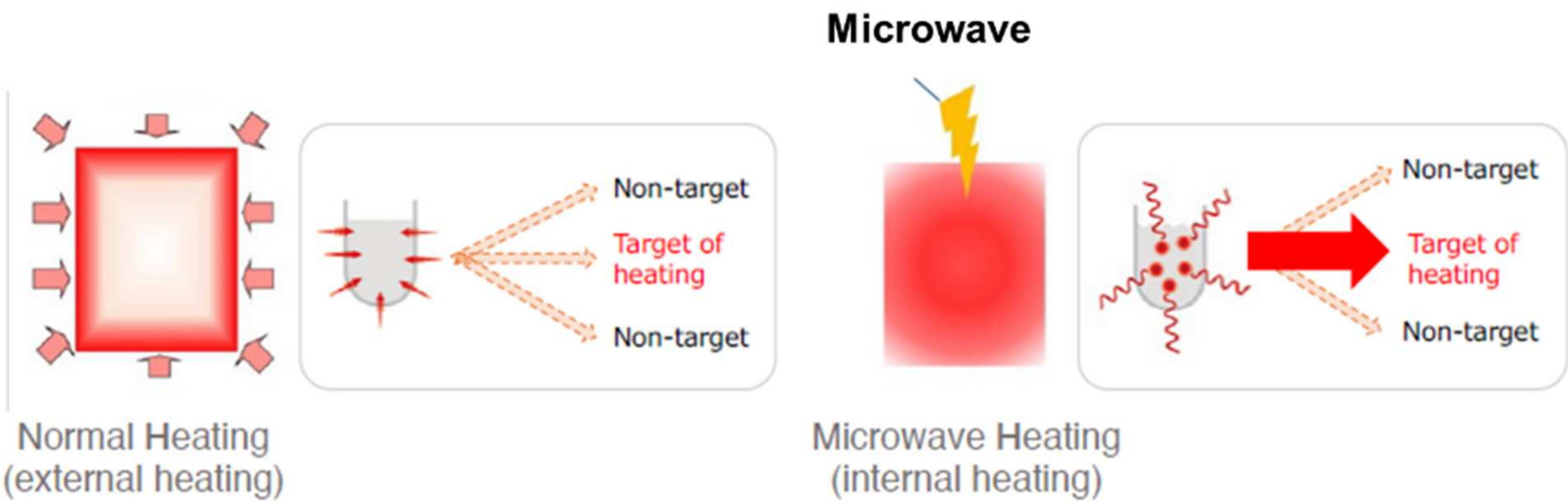
Benefits of RF Energy Applications



Summary : Highly Effective Energy Transfer Method

Microwave transfers energy to the only target material

directly, selectively and rapidly



Thank you

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