Materials science of electronic and optoelectronic devices

Yutaka Oyama

Optical fiber network in Japan&Worldwide

Background: activities in Tohoku University

Semiconductor laser (1957)

Light source

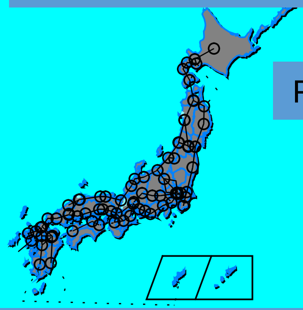
Optical fiber
Graded Index fiber (1964)

propagation

Avalanche photodiode
pin photodiode (1950)

detection

Optical fiber network (NTT)



Fiber network (domestic)

Oversea cable

Pacific ocean

Total length 13200km

Fiber To The Home(FTTH)

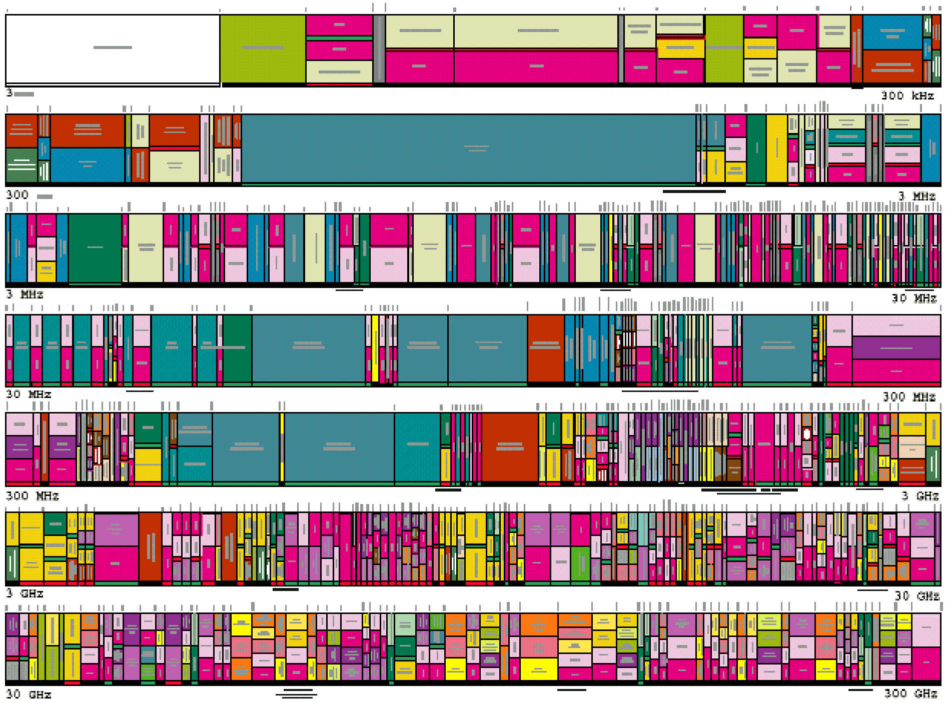
Fiber cable under the sea
(Kagoshima-Okinawa 1000km)

Multi-media new frontier

国際コンピュータネットワーク
放送・通信ネットワーク

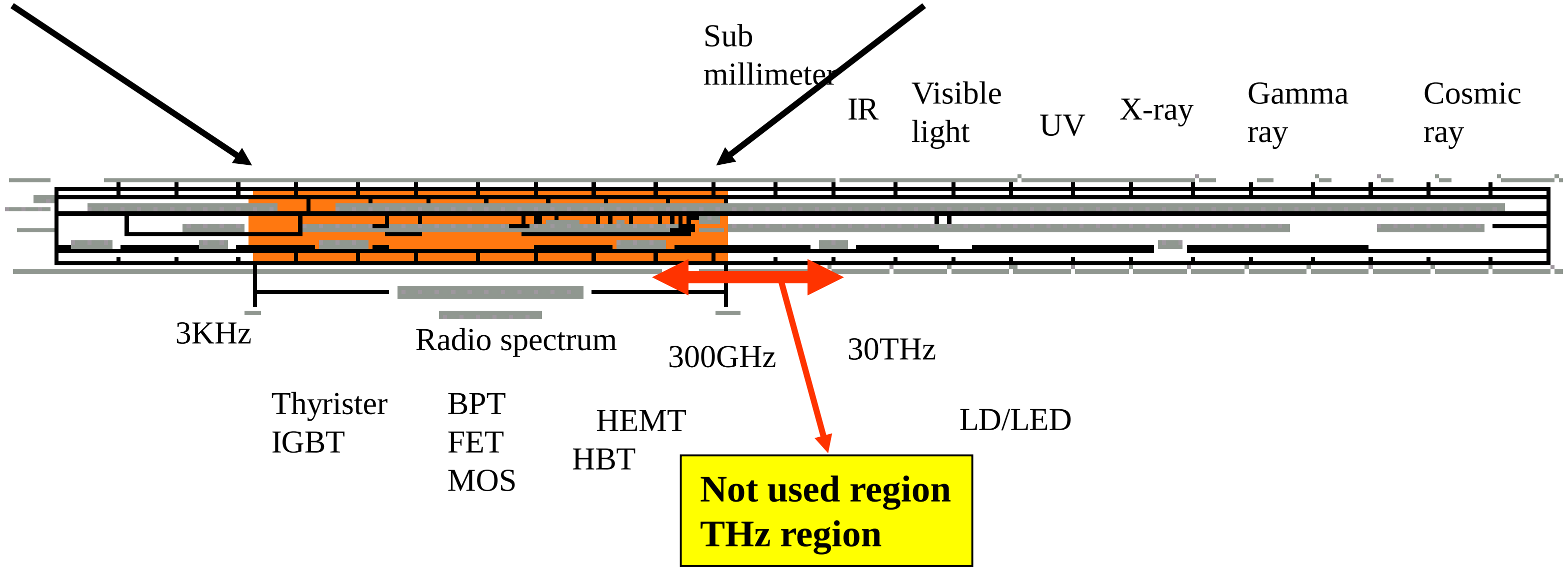
国際金融情報ネットワーク

Frequency Allocation (USA)

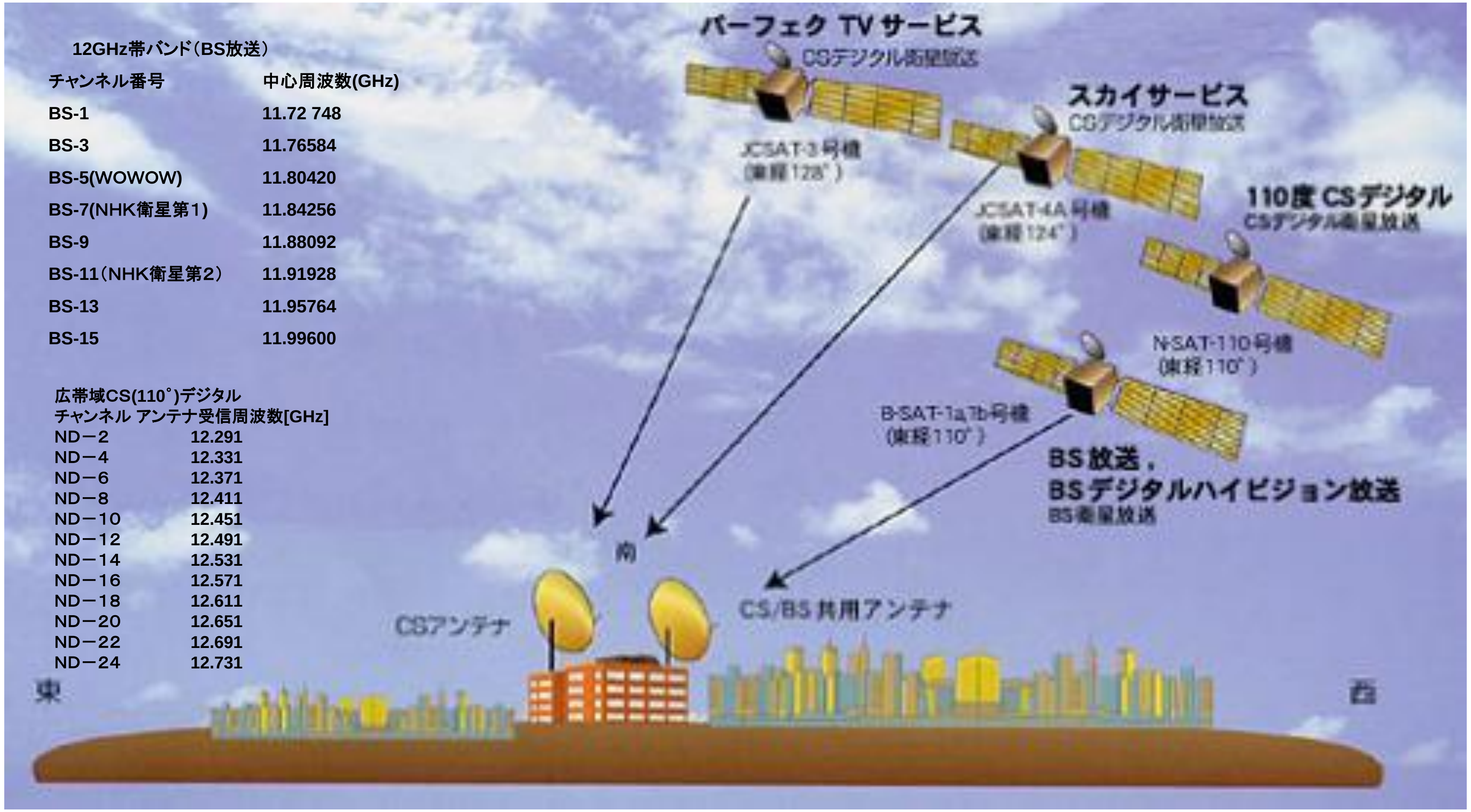


Our target device for not-used THz region

ISIT
TUNNETT
(Semiconductor Raman laser) -30THz



BS,CS bands from satellite to the earth

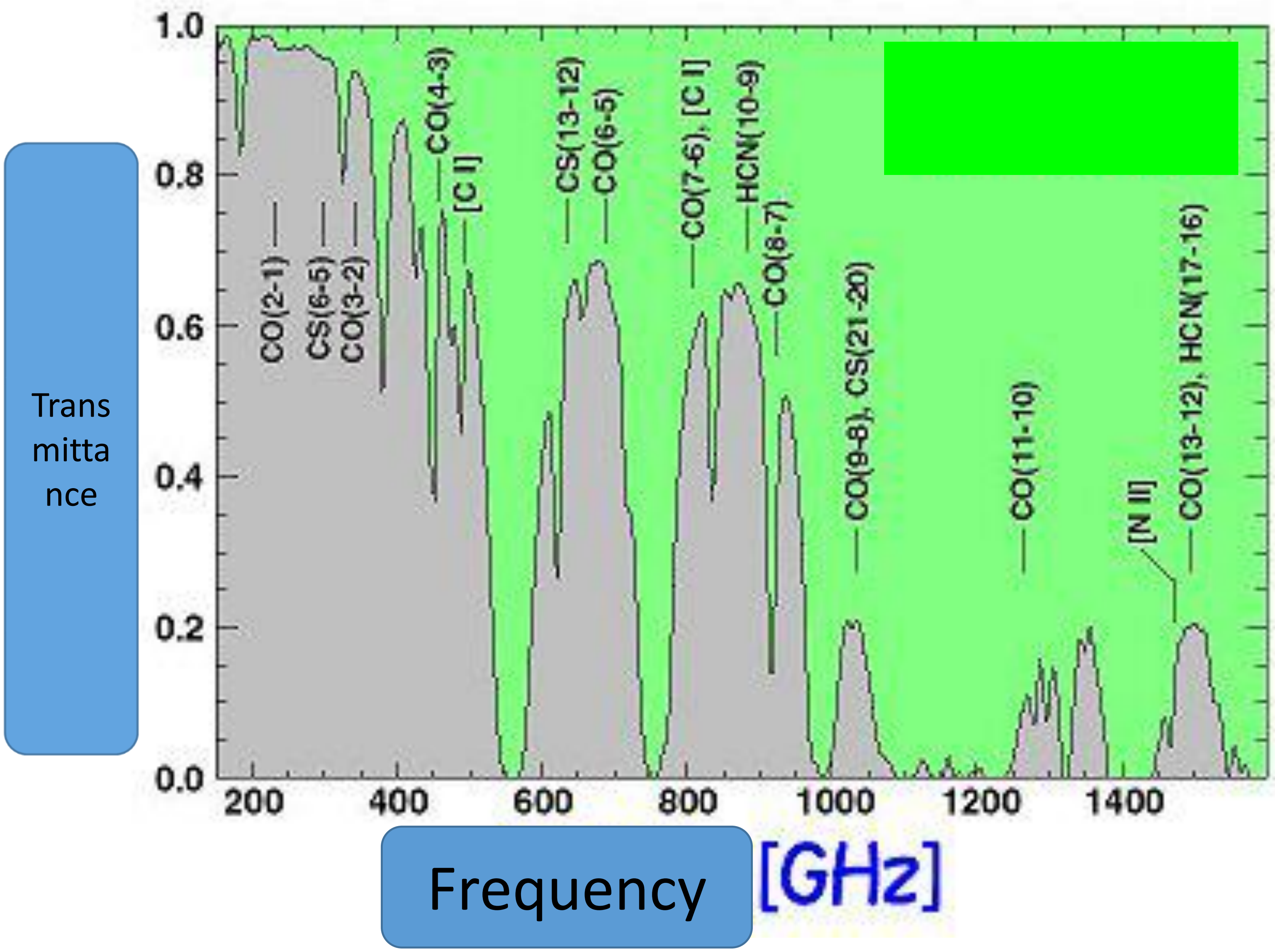


12GHz帯バンド（BS放送）

チャンネル番号	中心周波数(GHz)
BS-1	11.72 748
BS-3	11.76584
BS-5(WOWOW)	11.80420
BS-7(NHK衛星第1)	11.84256
BS-9	11.88092
BS-11（NHK衛星第2）	11.91928
BS-13	11.95764
BS-15	11.99600

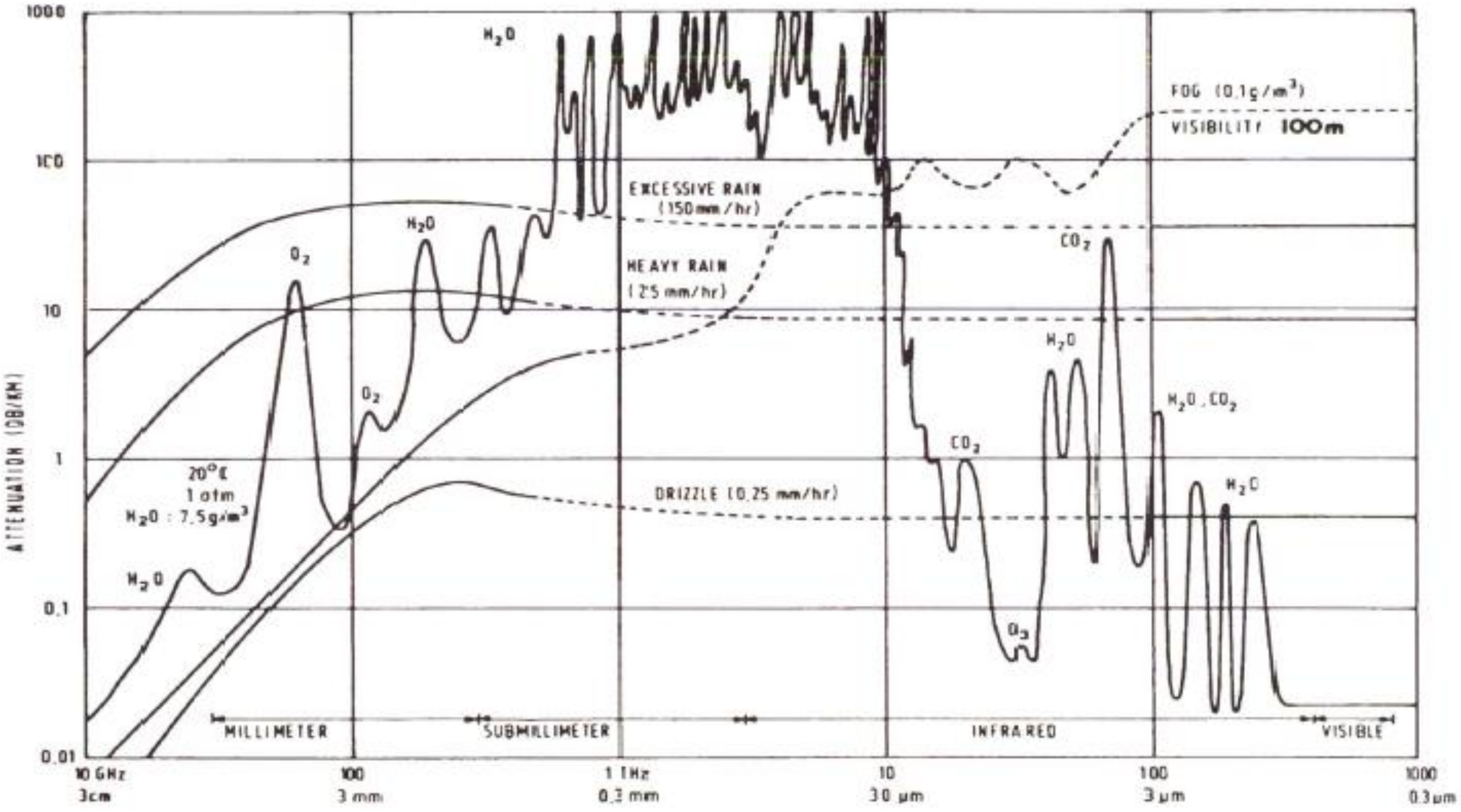
広帯域CS(110˚)デジタル

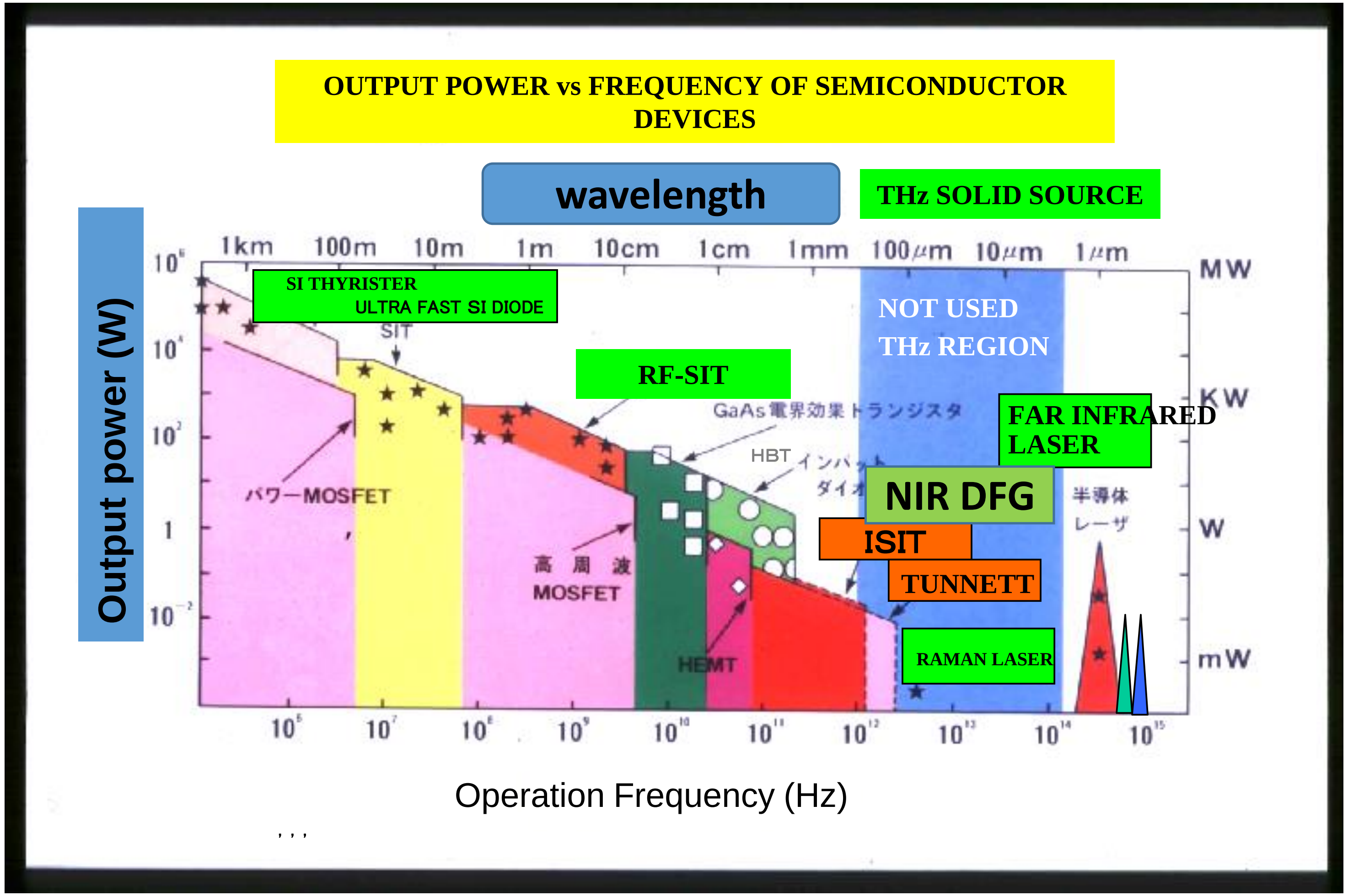
チャンネル	アンテナ受信周波数[GHz]
ND－2	12.291
ND－4	12.331
ND－6	12.371
ND－8	12.411
ND－10	12.451
ND－12	12.491
ND－14	12.531
ND－16	12.571
ND－18	12.611
ND－20	12.651
ND－22	12.691
ND－24	12.731



1.0
0.8
0.6
0.4
0.2
0.0
200
400
600
800
1000
1200
1400
CO(2-1)
CS(6-5)
CO(3-2)
CO(4-3)
[C I]
CS(13-12)
CO(6-5)
CO(7-6), [C I]
HCN(10-9)
CO(8-7)
CO(9-8), CS(21-20)
CO(11-10)
[N II]
CO(13-12), HCN(17-16)
Trans
mitta
nce
Frequency
[GHz]

Detailed attenuation characteristics in Air





*NIR DFG: Near Infrared laser induced Differential Frequency Generation
*ISIT: Ideal static induction transistor
*TUNNETT: Tunnel injection transit time effect diode

TARGET DEVICES

- (orange) → TODAY'S ISSUE
- (green) → LAB'S TARGET DEVICES

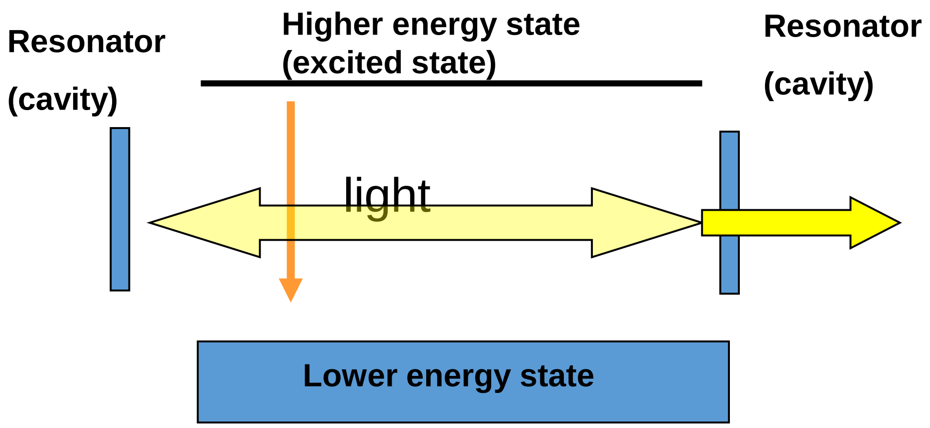
LASER

Light **A**mplification by **S**timulated **E**mission of **R**adiation

From **MASER** (Microwave Amplification by Stimulated Emission of Radiation

light ⇒ Spontaneous Emission

Stimulated emission



Energy distribution of electron

Fermi-Dirac distribution

負の温度

Equilibrium⇔spontaneous
熱平衡状態 自然放出

Negative temperature distribution （inversion） ⇔ stimulated （誘導放出） emission

Laser is composed with
Laser material, a set of parallel mirror (cavity)

Methods to realize the inversion distribution（**反転分布**）

Flash lamp (solid laser etc.)
Electron injection（semiconductor laser: LD）
Gas discharge（gas laser）
LD excitation

Phase term

$$A = A_0 \cos\left(\overbrace{\frac{2\pi}{\lambda} z - 2\pi \nu t + \alpha} \right)$$

Characteristic feature of laser

Coherent :interference due to well defined phase

Directional: parallel beam

Monochromatic light due to resonance

High energy density

$$n\lambda = 2L$$

Three principle components for optical communication

光通信三要素

Glass fiber

Graded index fiber, (Tohoku univ.)
Step index fiber
Prastic fiber
IR transmission
RF transmission

Light source → Propagation line → Light detector

Semiconductor laser
(semiconductor maser: Tohoku univ.)
Light emitting diode

***pin* photo diode** (fast response)
Avalanche photo diode (high sensitive amplification)
Tohoku Univ.

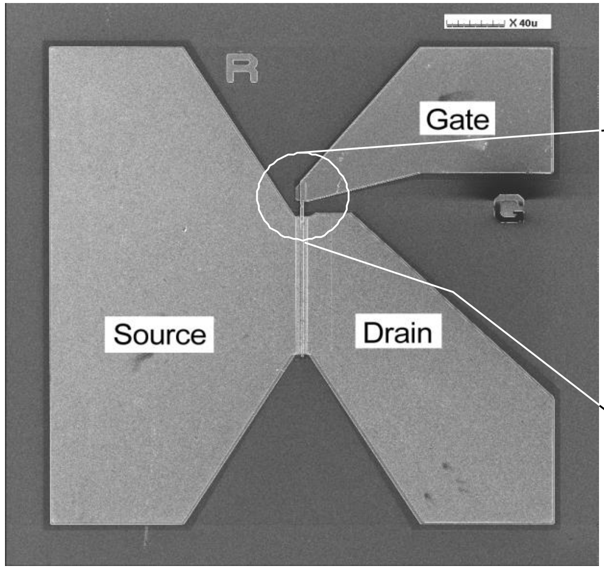
modulation

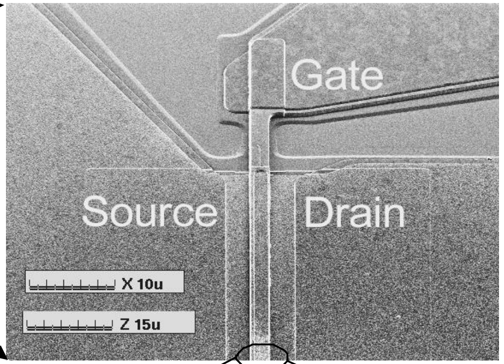
Static Induction Transistor (Tohoku Univ.)

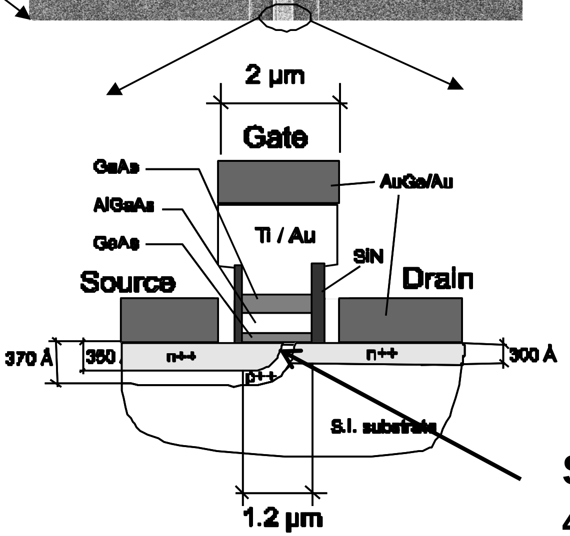
demodulation

Static Induction Transistor
Semiconductor Raman Laser

S/D 4nm Transistor for THz freq.







Source/Drain 4nm

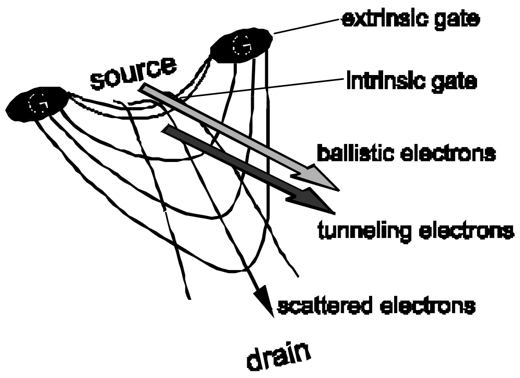
Transit time due to ballistic electron transport

$$t_{transit} \approx 2l_{ch}\sqrt{\frac{m^*}{2qV_{DS}}}$$

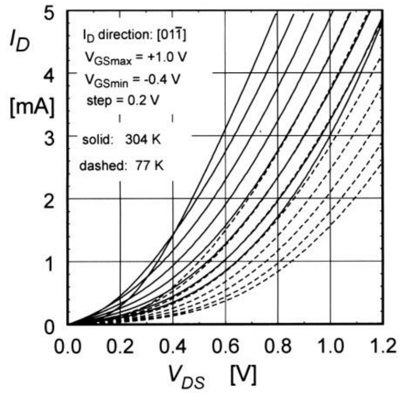
$$\leq 0.16\ ps$$

4nm channel length transistor structure

operation principle of ISIT



- induced potential barrier
- gate: homojunction or heterojunction or MIS
- potential barrier modulated with gate potential but also with drain potential

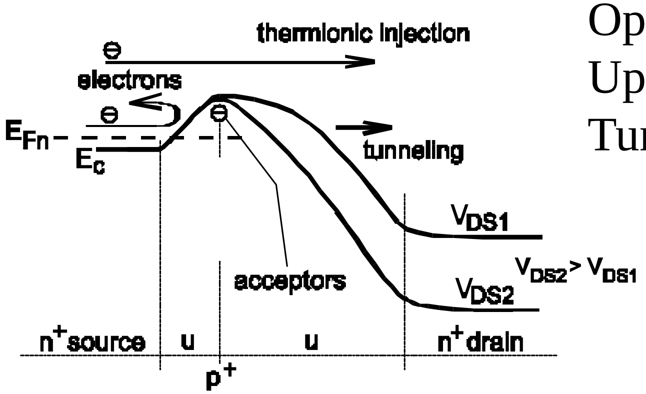


$$J_D \approx \gamma_F A^* T^2 \exp\left[q \frac{-\Psi_0 + \eta\left(V_{GS} + \frac{V_{DS}}{\mu_F^*}\right)}{k_B T} \right]$$

From Bethe theory (thermo ionic emission)

Ballistic electron transport

No scattering of electrons with lattices



Operation frequency (estimated)

Up to 800GHz (0.8THz)

Tunnel transport

$$\gamma_F \approx \frac{I_s h^3}{4\pi q m_t^* k_B^2 T^2}$$

Ballistic electron injection efficiency

$$\frac{J_{SD}(tunnel)}{J_{SD}(therm-ionic)} \approx \frac{(E_F - E_C)^2 \exp\left[\left(-\frac{2m^*(\Psi_B - E_F)w}{3h}\right)\right]}{2k_B^2 T^2 \exp\left(-\frac{\Psi_B - E_C}{k_B T}\right)}$$

From Simmons theory, WKB approximation

✧**ISIT(Ideal Static Induction Transistor)**
invented in 1979 by J.Nishizawa
(J. Nishizawa, Proc. 1979 IEEE Int. Conf. Solid State Devices, 1979.)Washington DC

$$w_{tunnel} \approx \frac{3h}{8\pi\sqrt{2m^*(\Psi_B - E_F)}}\left[\frac{\Psi_B - E_C}{k_B T} - \ln\left(\frac{2k_B^2 T^2}{(E_F - E_C)^2}\right)\right]$$

Tunnel injection dominated condition
GaAs 25nm (RT)
90nm (77K)
Case: $\Psi_B - E_C$ 0.855V
E_F-E_C=0.15eV

Categories of semiconductor devices

Electron transport devices

Electronic devices

Electric vehicle

Super express train (inverter control)

Thyristor, power diode, IGBT(Insulating gate bipolar transistor)

- **Low power consumption devices**

  Mobile phones, pad

  MOS(Metal Oxide Semiconductor) device

  GaAs FET

- **High frequency (RF) devices**

  Microwave telecommunication

  High speed CPU

  Satellite broadcast

  Short channel MOS

  HEMT, HBT device

  NRD device

  TUNNETT, ISIT

  IMPATT, GUNN

HEMT	(High Electron Mobility Transistor)
FET	(Field Effect Transistor)
HBT	(Hetero Bipolar Transistor)
TUNNETT	(Tunnel injection Transit Time effect diode)
ISIT	(Ideal Static Induction Transistor)
NRD	(Negative Resistance Diode)
IGBT	(Insulated Gate Bipolar Transistor)

Opto devices
(optoelectronics)

Light
emission

Wavelength

Far IR	**PbTe, QCLD(quantum cascade LD)**
Near IR	**InGaAs .....**
Visible	**AlGaAs, InGaAlP ......**
Blue	**InGaN, SiC, ZnO**
UV	**GaN, Diamond**

Semiconductor laser (LD)
(laser diode:LD)

- Optical telecommunication
- DVD CD writer/pickup
- Welding (high power)

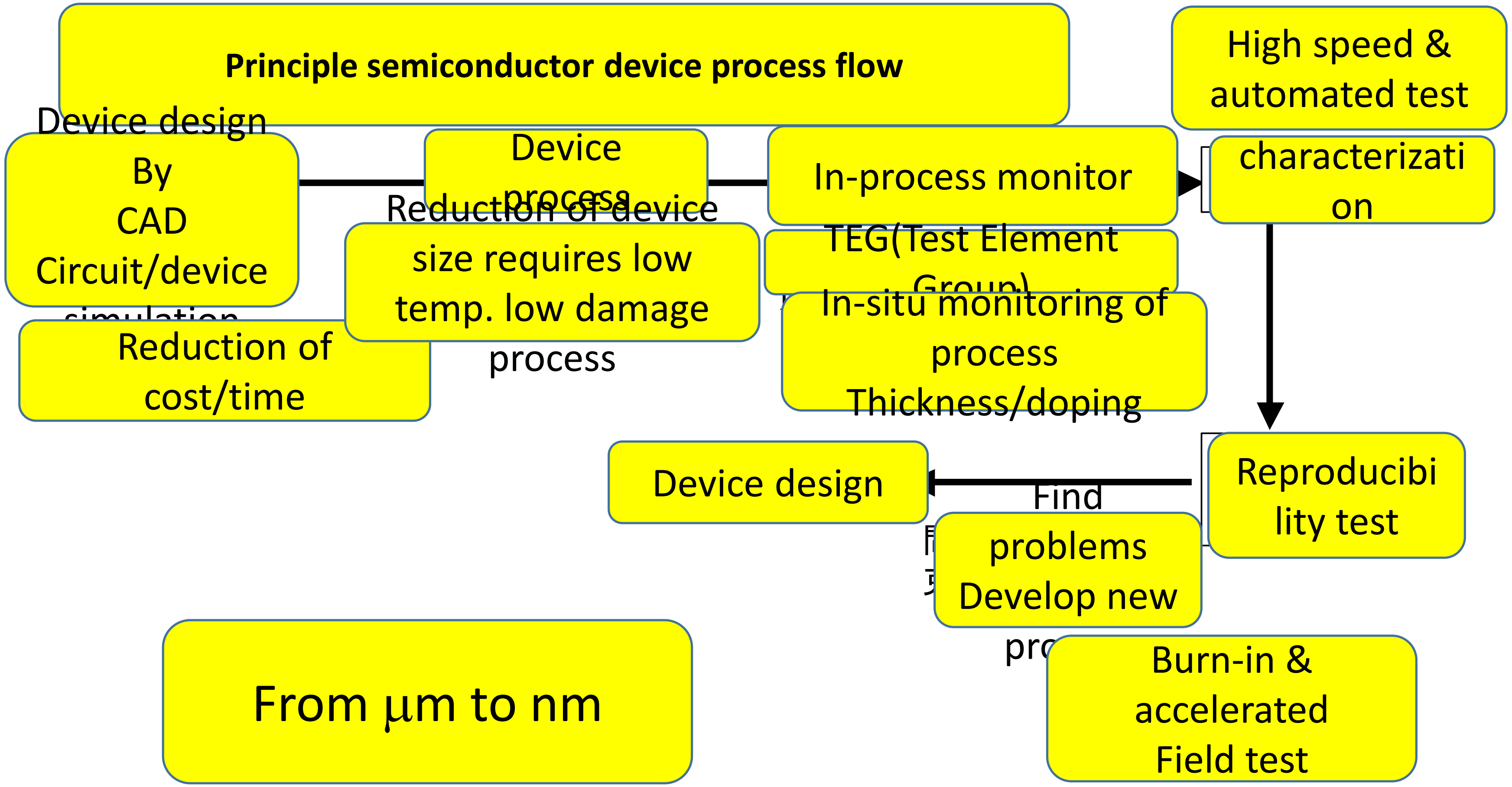
- Simple edge emitting LD(stripe LD)
- Quantum well LD
- Surface emitting LD (vertical cavity LD)
- Quantum cascade LD
- Multi-stripe LD(high power)

Light emitting diode (LED)

- Indicator

Light detection

Pin, avalanche diode
Quantum well/dot detector



Principle semiconductor device process flow
Device design
By
CAD
Circuit/device
simulation
Reduction of
cost/time
Device
process
Reduction of device
size requires low
temp. low damage
process
In-process monitor
TEG(Test Element
Group)
In-situ monitoring of
process
Thickness/doping
High speed &
automated test
characterizati
on
Reproducibi
lity test
Device design
Find
problems
Develop new
Burn-in &
accelerated
Field test
From μm to nm

Principle device elements of semiconductor devices

Device structures

↑

Metal, Semiconductor, Insulator (Ceramics)

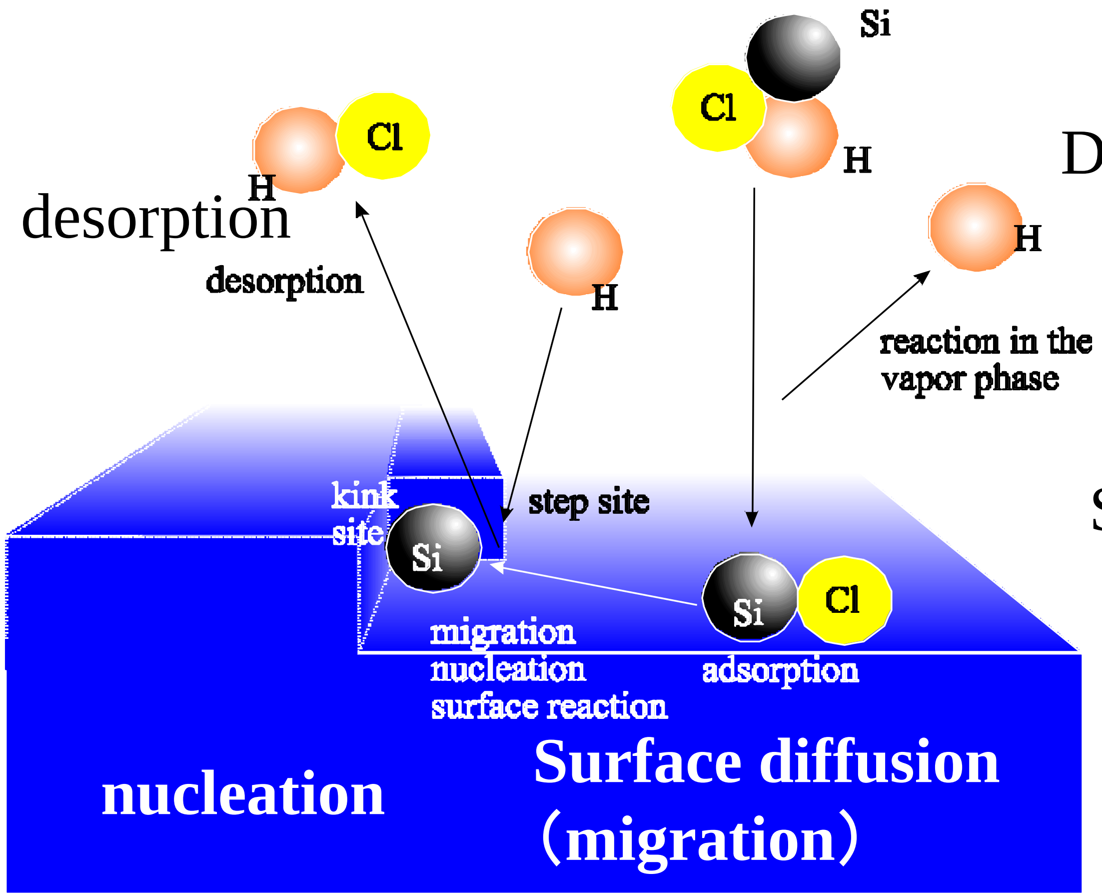
Semiconductor →

Single crystal material

Others
Amorphous (TFT Tr. LCD driver)
Polycrystalline (solar cells)
Organic semiconductors

Detailed reaction processes of Epitaxial growth

Vapor phase or solution reaction



Diffusion to the surface

Surface adsorption

Surface reaction

Real surface reaction process in MLE Si

Si_react

半導体デバイスは、「**金属・半導体・セラミックス**」を総合して形成。
理想型静電誘導トランジスタのプロセス例

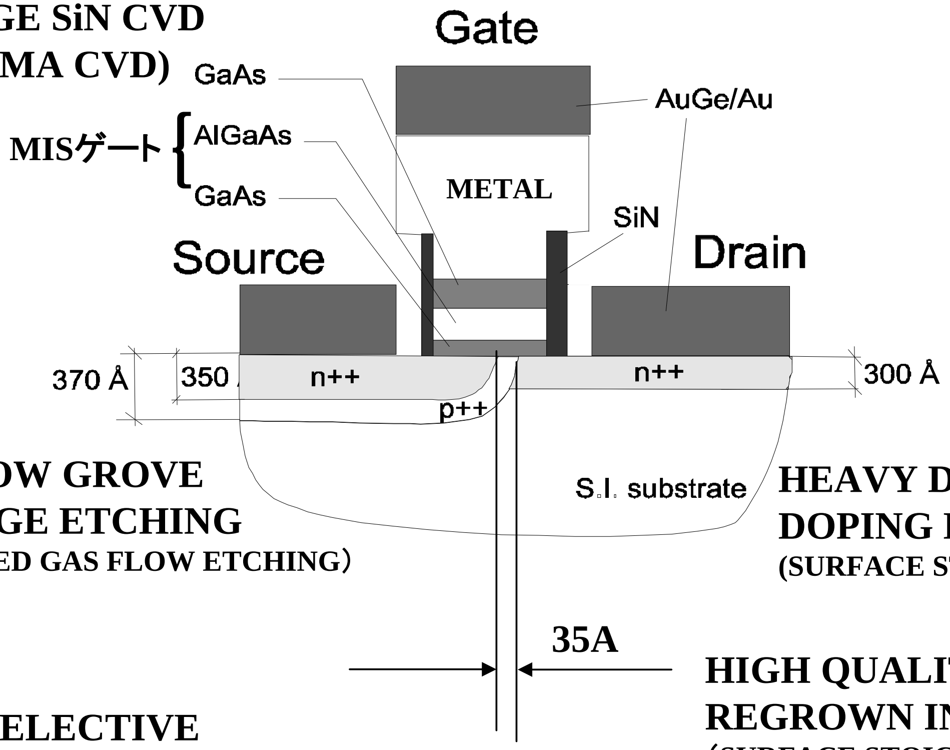
DETAILED CRITICAL PROCESSES FOR ISIT

METAL/CERAMICS/SEMICONDUCTOR BREAKTHROUGH PROCESSES

SELECTIVE EPITAXY
（SELF-ALIGN PROCESS）

LOW ρ_c CONTACT（METAL/SEMI CONTACT）
NON-ALLOYED
VERY THIN MIXED LAYER

LOW-T&DAMAGE SiN CVD
（REMOTE PLASMA CVD）

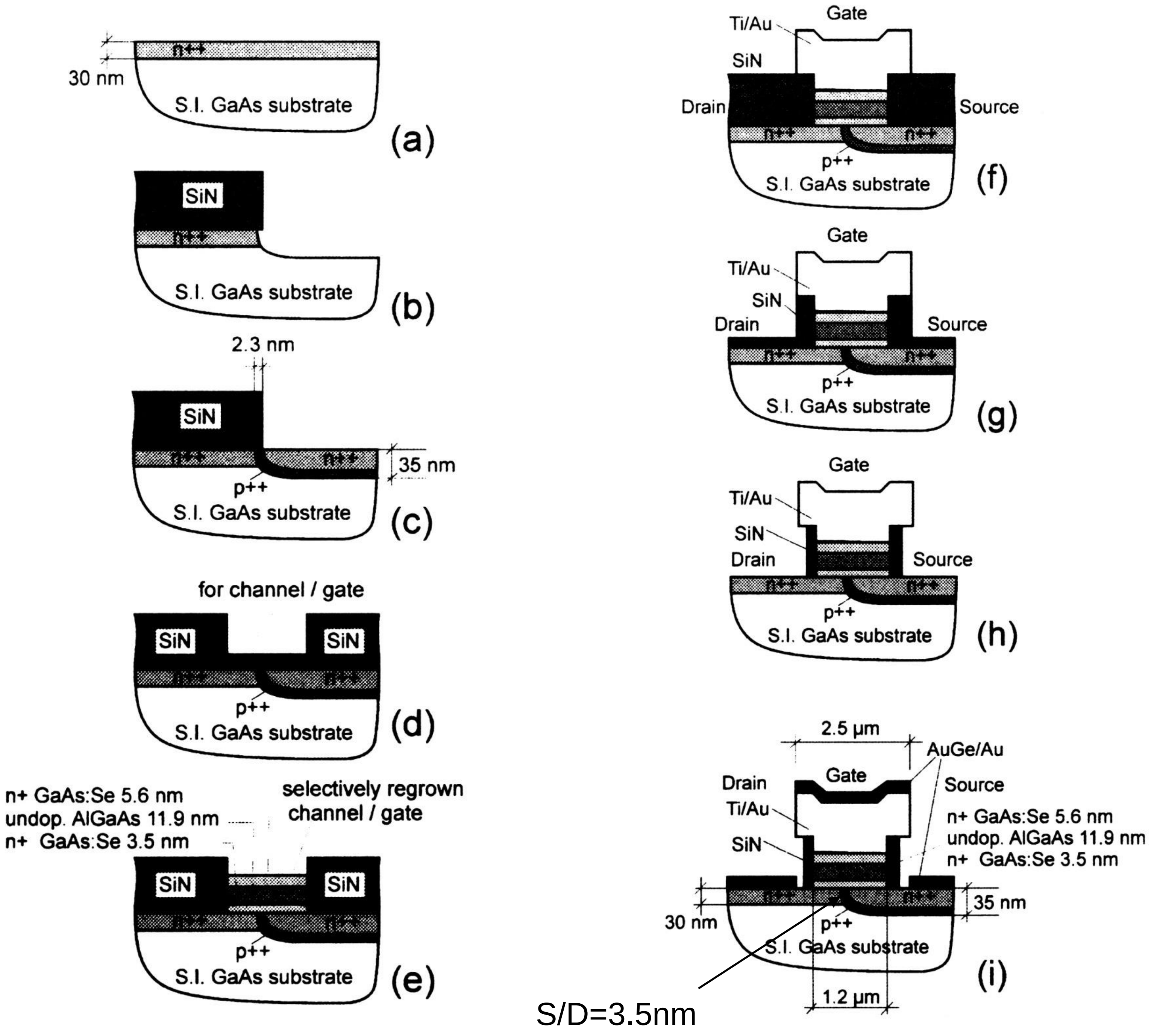


ULTRA SHALLOW GROVE
LOW-T&DAMAGE ETCHING
（PHOTO-STIMULATED GAS FLOW ETCHING）

HEAVY DOPING
DOPING EPITAXY 10^{19}-10^{20}cm^{-3}
(SURFACE STOICHIOMETRY CONTROL)

HIGH QUALITY
REGROWN INTERFACE
（SURFACE STOICHIOMETRY CONTROL）

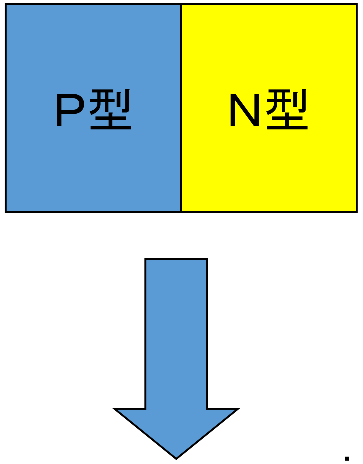
LOW-T& SELECTIVE
MOLECULAR LAYER EPITAXY (MLE)
WITH ATOMIC ACCURACY (AA)


30 nm
n++
S.I. GaAs substrate
(a)
SiN
n++
S.I. GaAs substrate
(b)
2.3 nm
SiN
n++
n++
35 nm
p++
S.I. GaAs substrate
(c)
for channel / gate
SiN
SiN
n++
n++
p++
S.I. GaAs substrate
(d)
n+ GaAs:Se 5.6 nm
undop. AlGaAs 11.9 nm
n+ GaAs:Se 3.5 nm
selectively regrown
channel / gate
SiN
SiN
n++
n++
p++
S.I. GaAs substrate
(e)
Gate
Ti/Au
SiN
Drain
Source
n++
n++
p++
S.I. GaAs substrate
(f)
Gate
Ti/Au
SiN
Drain
Source
n++
n++
p++
S.I. GaAs substrate
(g)
Gate
Ti/Au
SiN
Drain
Source
n++
n++
p++
S.I. GaAs substrate
(h)
2.5 µm
AuGe/Au
Drain
Gate
Source
Ti/Au
n+ GaAs:Se 5.6 nm
undop. AlGaAs 11.9 nm
n+ GaAs:Se 3.5 nm
SiN
n++
n++
35 nm
30 nm
p++
S.I. GaAs substrate
(i)
1.2 µm
S/D=3.5nm

pin diode

Rectification･demodulation
（alternate curr. AC→direct curr. DC）

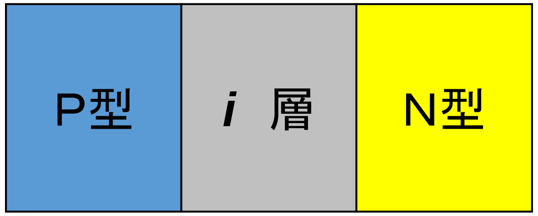
pn diode



Storage of minority carrier limits RF operation

Majority carrier in p-type: hole
minority carrier：electron
Majority carrier in n-type：electron
minority carrier：hole

pin diode



高抵抗
高純度*i*層

Carrier recombination in *i*-layer

Fast operation

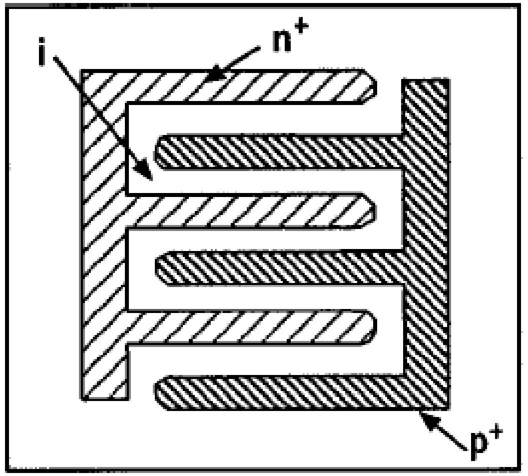
Insertion of high purity *i*-layer

High breakdown voltage

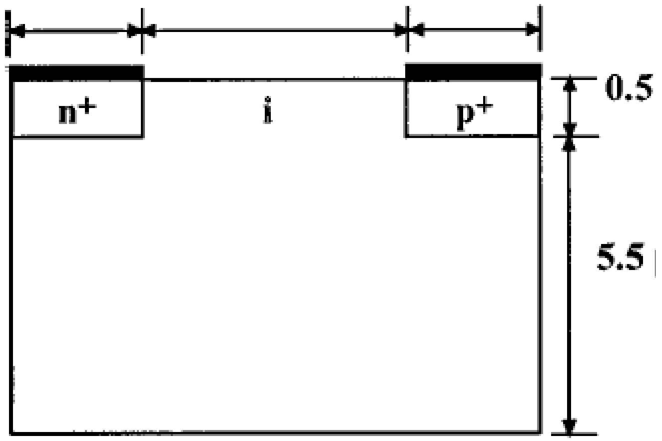
Photo detector application → Fast light detection

Lateral pin photo detector application

APL 1998, J. N. Haralson II, J. W. Parks, Jr., and K. F. Brennan



[a]



[b]

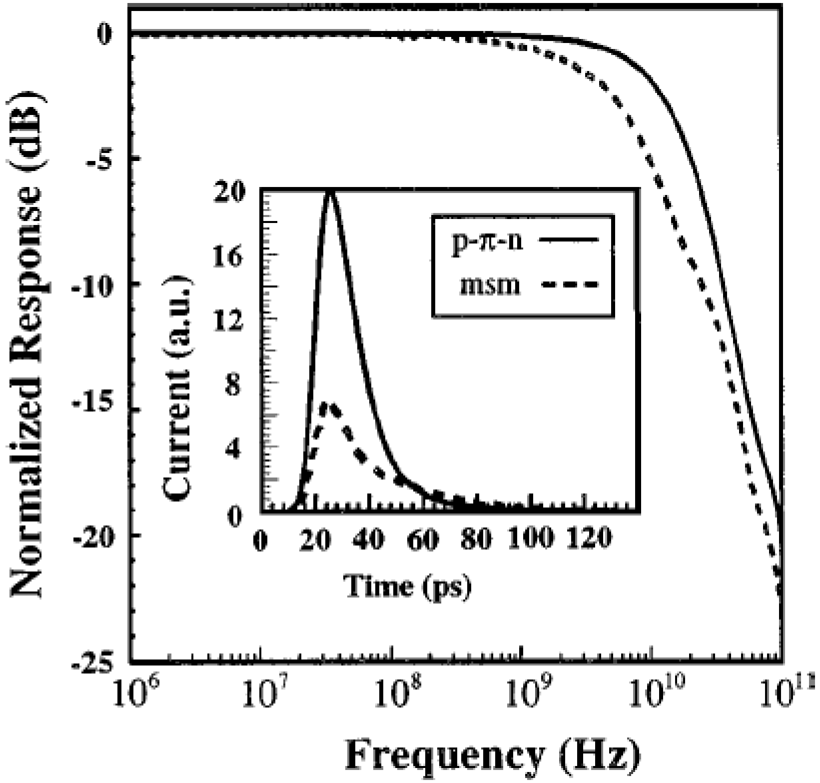
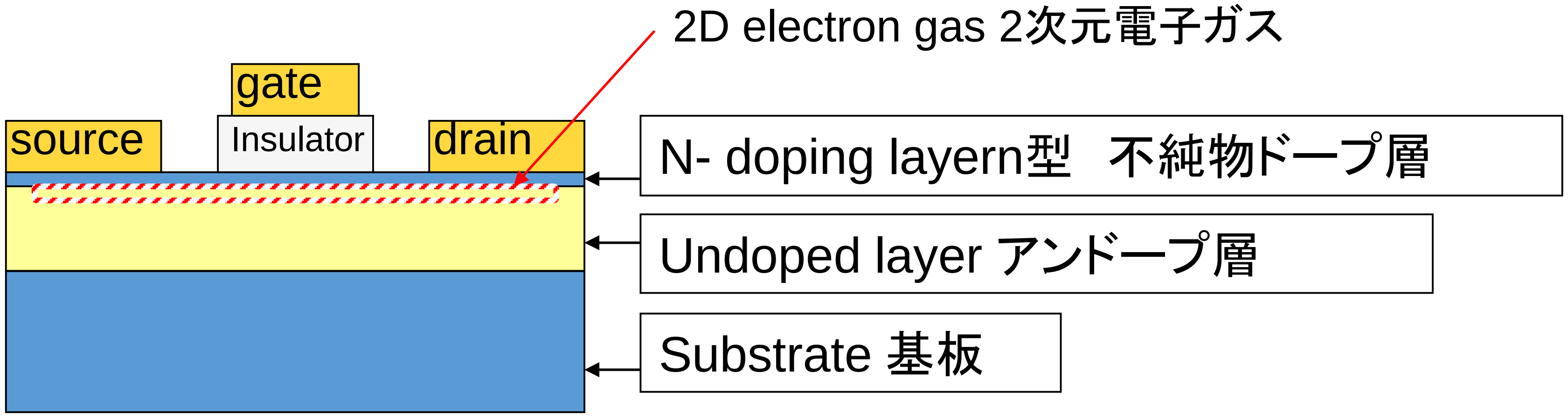


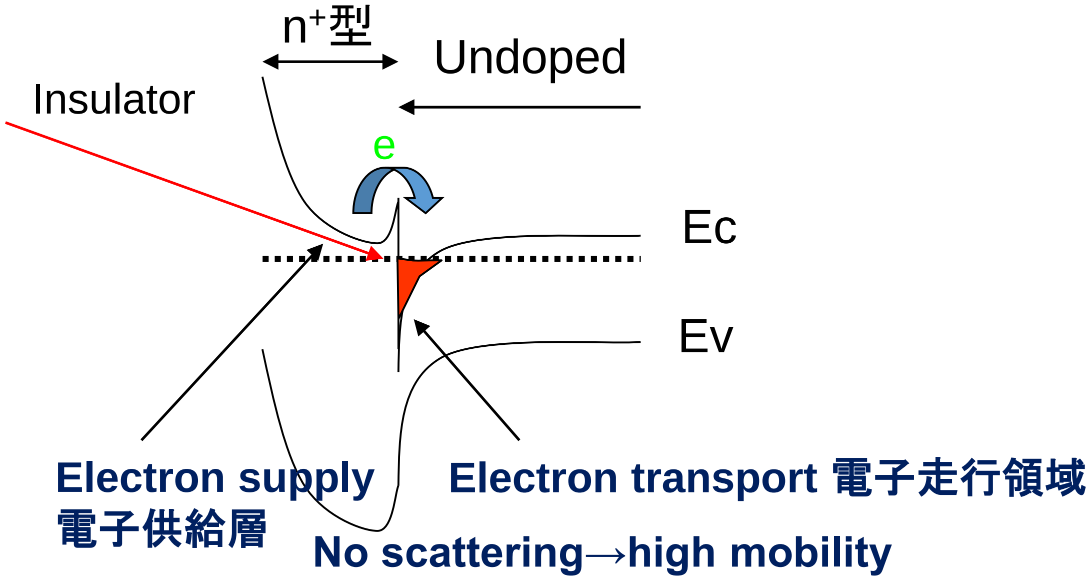
FIG. 2. Calculated frequency response in dB for the p-π-n LPIN and MSM photodetectors shown in Fig. 1. The inset shows the temporal response of the photodetectors showing the higher responsivities of the p-π-n structure compared to the MSM device.

HEMT(High Electron Mobility Transistor)

高電子移動度& 高キャリア濃度→高相互コンダクタンス g_m 高周波動作



Mechanism for high conductance
Carrier supply & carrier transport
⇒
Achievement of high carrier concentration &
High carrier mobility



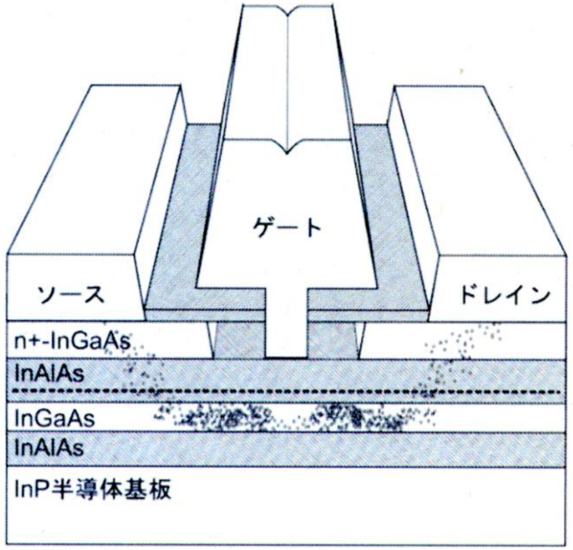


Fig.1 Structure of InP-HEMT

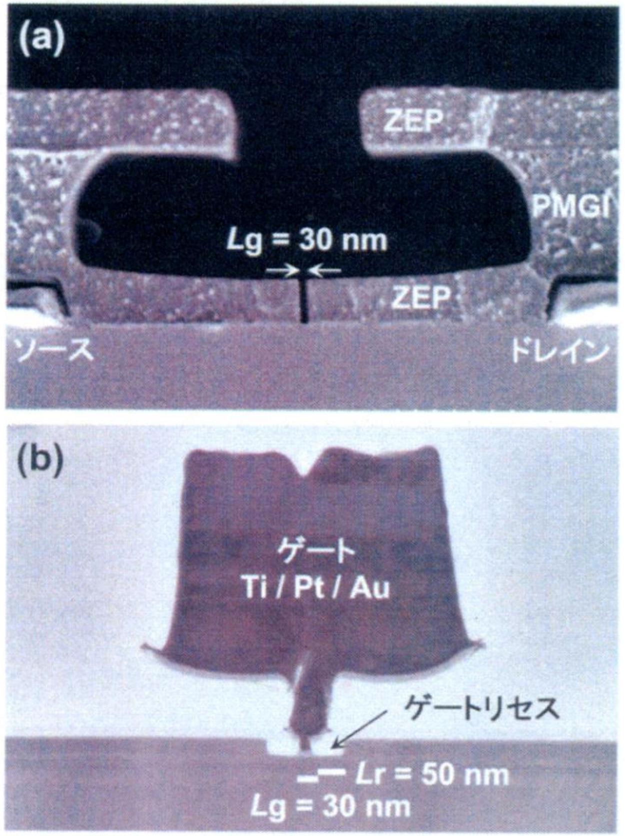


Fig.2 (a) SEM cross-sectional image of tri-layer resist immediately after development; (b) TEM cross-sectional image of T-shaped gate

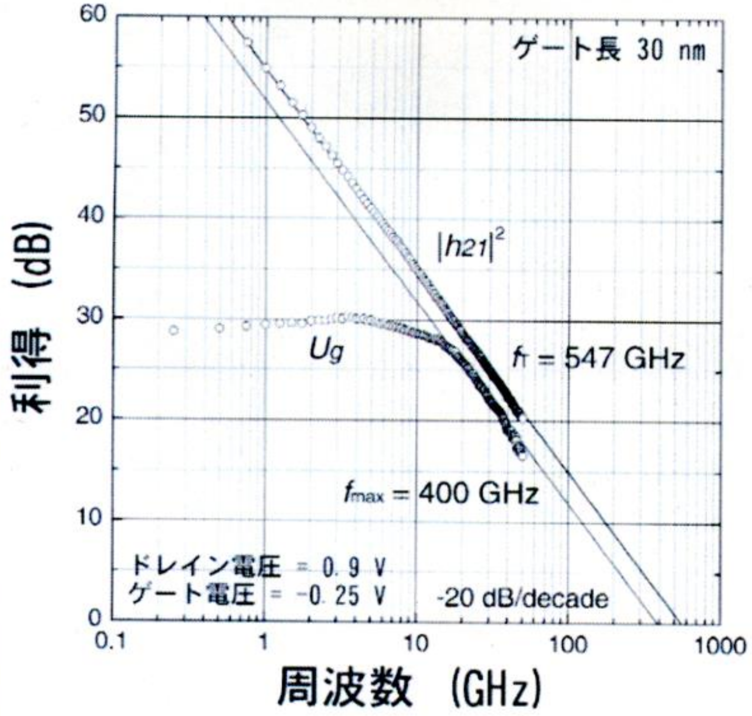


Fig.12 High-frequency performance of pseudomorphic-channel InP-HEMT with gate length of 30 nm and multi-layer cap structure

Ref; Nano-Gate Transistor — World's Fastest InP-HEMT — SHINOHARA Keisuke and MATSUI Toshiaki

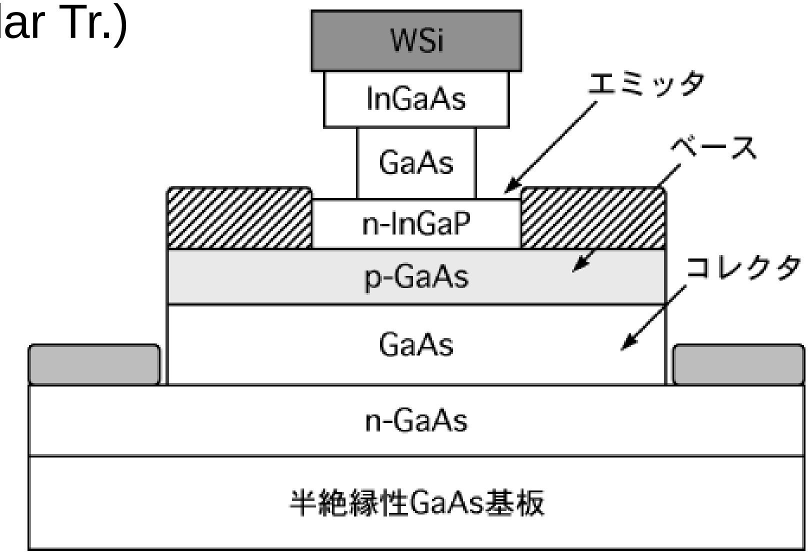
Journal of the National Institute of Information and Communications Technology Vol.51 Nos.1/2 2004

Mushroom gate

HBT(Hetero Bipolar Tr.)

Mobile phone base
RF high power
携帯･セルラーフォン
基地局用････

図-1　HBTの断面構造図

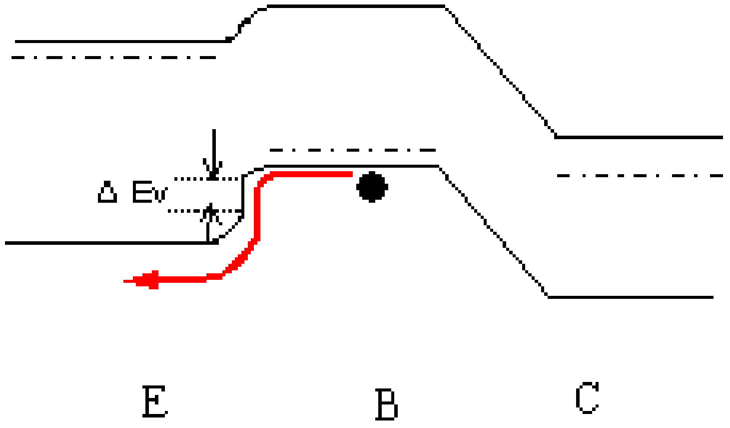


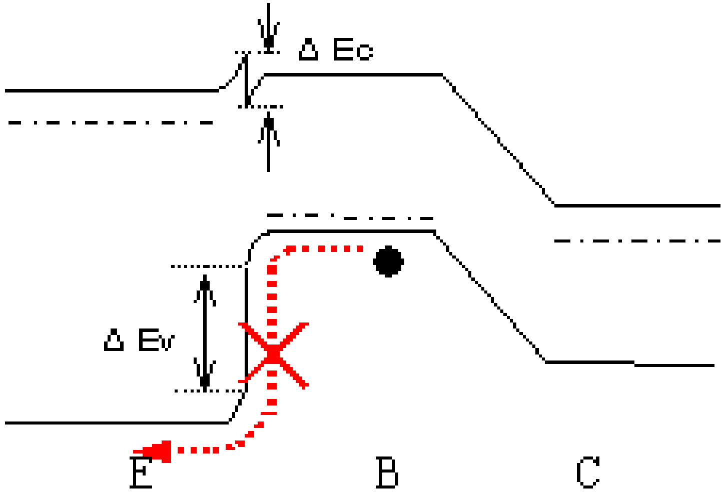
エミッター接地回路の**電流利得β**は、ベース電流に対するコレクター電流の比ですから、

$$\beta = \frac{\partial I_C}{\partial I_B} = \frac{\alpha}{1-\alpha}$$

ベース領域内で生じる再結合電流がエミッター領域に流れ込むことが電流増幅率βを下げる原因となりますから、ベース領域で発生する再結合電流が流れ込まないように、**ベースとエミッターの間にポテンシャルバリア(障壁)を作る**構造

$$\beta = \frac{\partial I_C}{\partial I_B} = \frac{\alpha}{1-\alpha}$$





Conventional bipolar Tr.

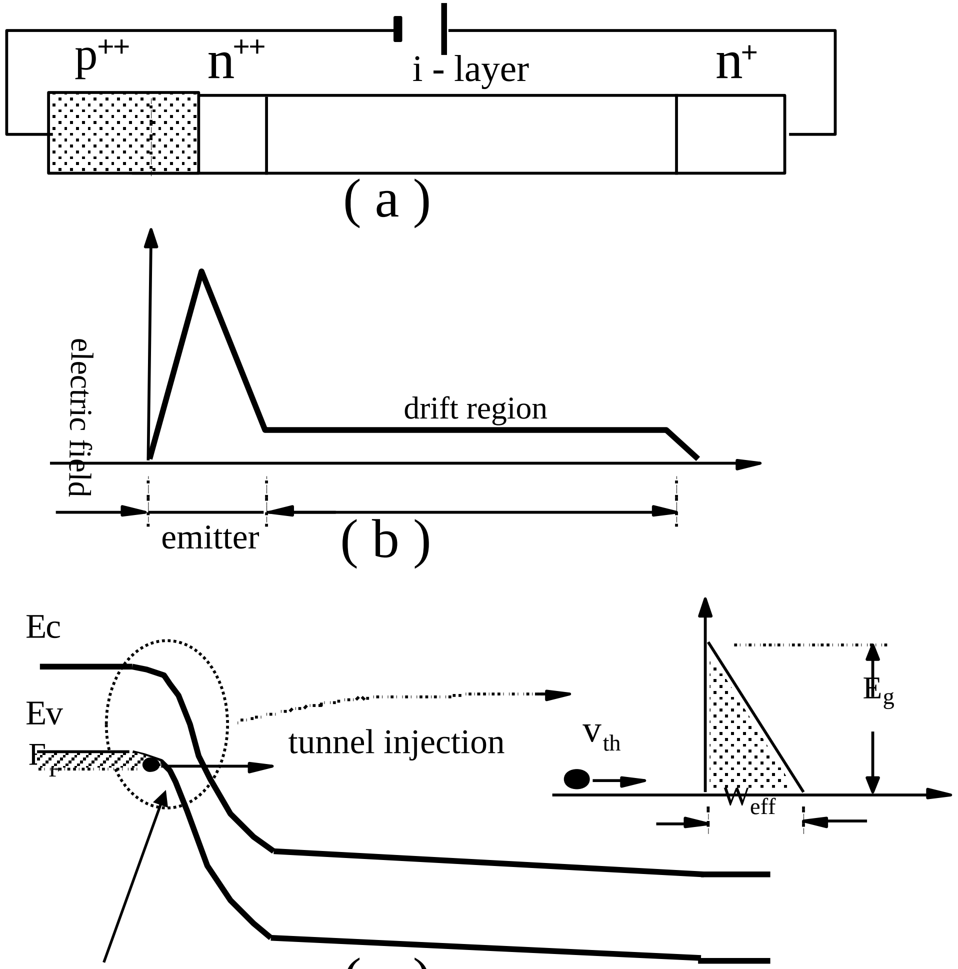
Hetero bipolar Tr.

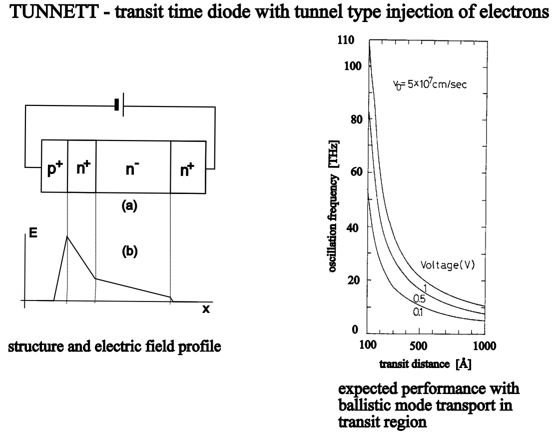
PRINCIPLE OF TUNNETT DIODE

TUNNETT:tunnel injection transit time effect diode

For THz oscillation solid source (invented by **J.Nishizawa Tohoku Univ.)**

Tunnel injection under reverse bias
low operating voltage
low noise



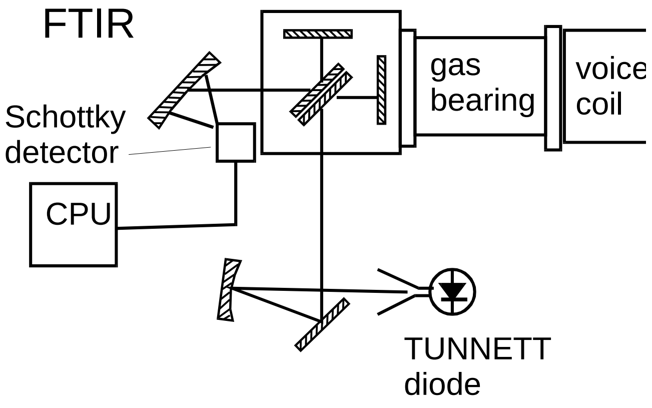


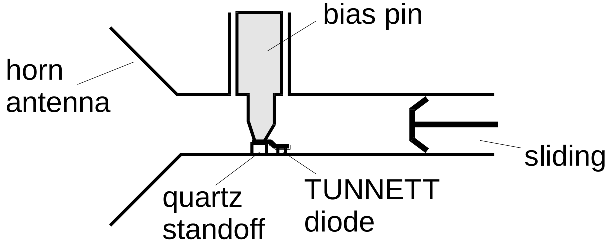
$p^{+}n^{+}$ tunnel injection layer requires
Very thin (nm) n^{+} layer with atomic accuracy
with very steep impurity profile

Application of MLE

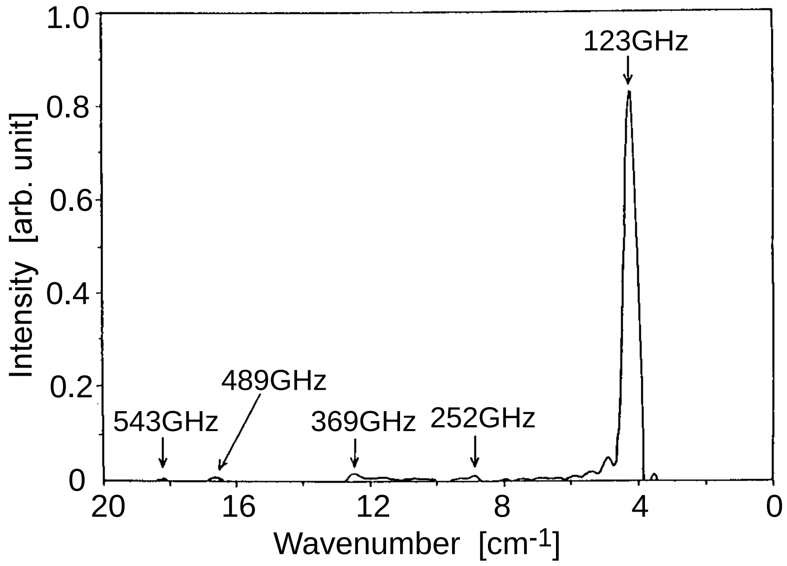
●*Performance in brief*
✧*TUNNETT*

TUNNETT oscillation measured with FTIR





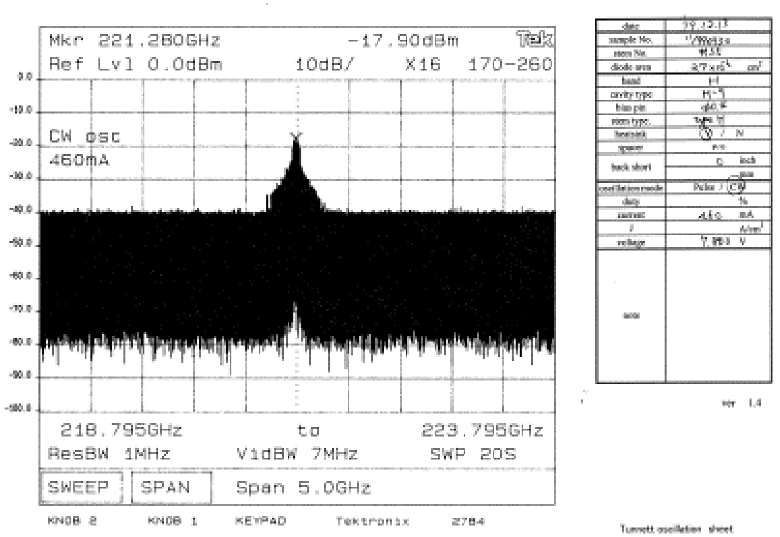
TUNNETT oscillator in a waveguide cavity coupled to a horn antenna



oscillation spectra

●*Performance in brief*

✧*TUNNETT*



221 GHz, MLE wafer, H-band cavity

Phase noise
-70dBc/Hz
(1KHz)

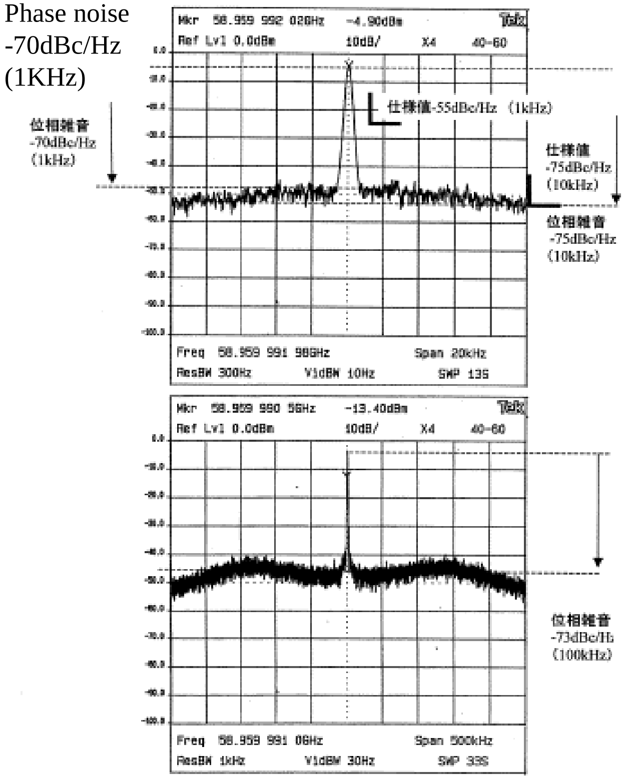


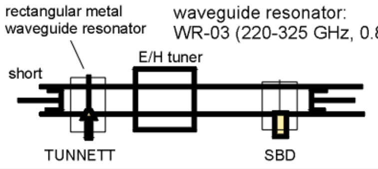
図2 58.96GHz 発振器位相雑音特性

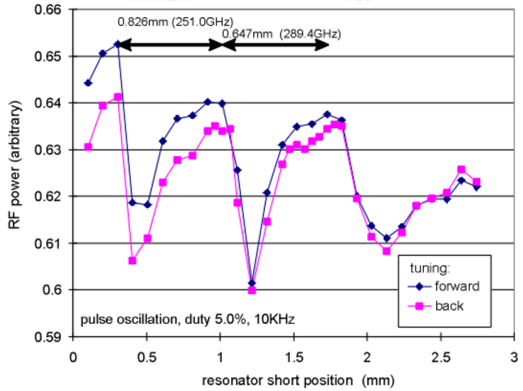
Phase noise
-73dBc/Hz
(100KHz)

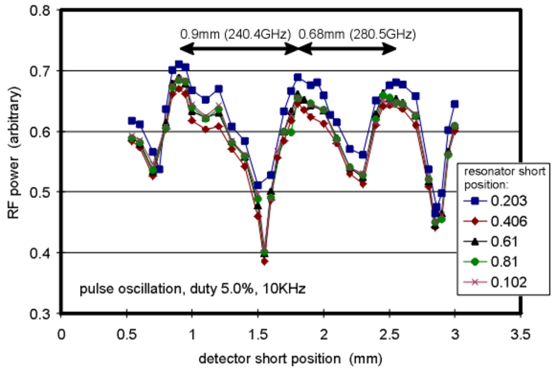
60GHz TUNNETT phase noise characteristics
with PLL phase-rock
V-band cavity

TUNNETT oscillator tuning

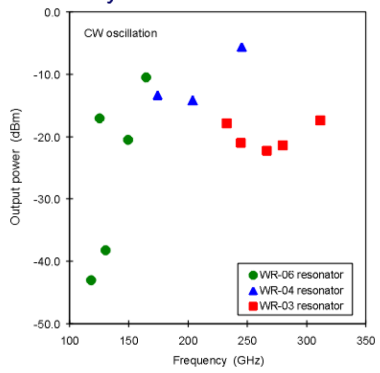
waveguide resonator:
WR-03 (220-325 GHz, 0.86×0.43 mm)





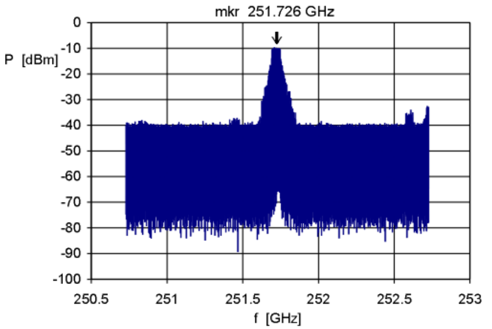


One TUNNETT structure in different resonator cavities - max. frequency limited by cavity Q not by GaAs structure



oscillation in WR-04 cavity

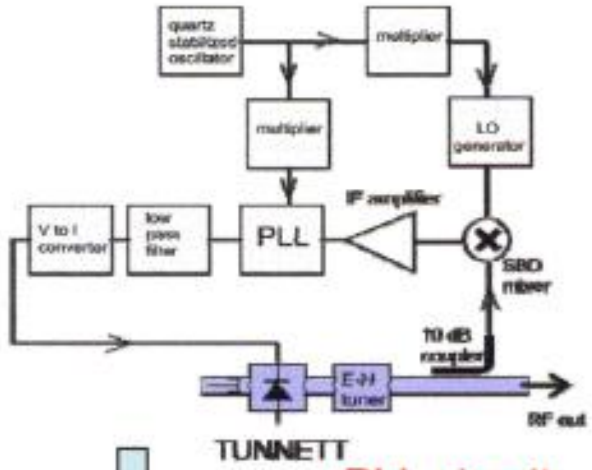
WR-04 (170-260 GHz) rectangular waveguide cavity
TUNNETT CW operation, 160 mA, 1.47e4 A/cm^2, 10.5 V bias



from 250.780 GHz to 252.780 GHz

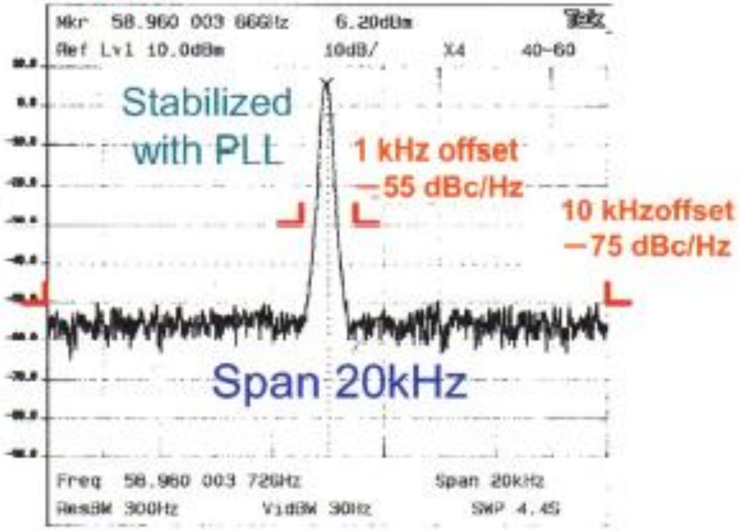
ResBW 1 MHz VidBW 7 MHz SWP 10 s Span 2.0 GHz

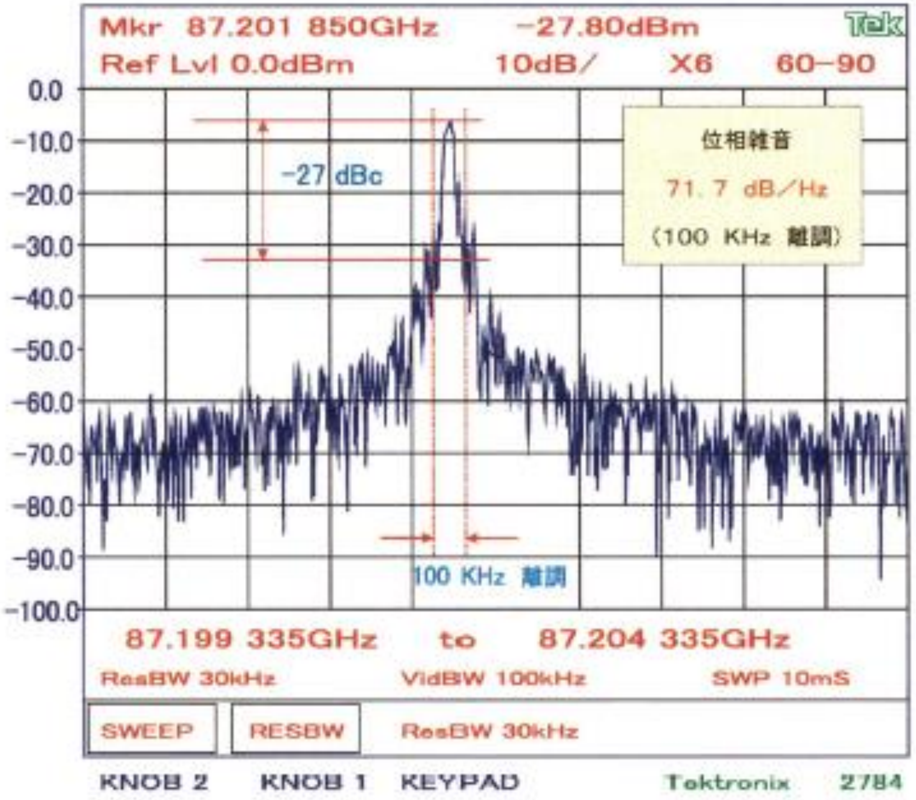
TUNNETT Oscillator (with and without PLL)



PLL circuit

PLL

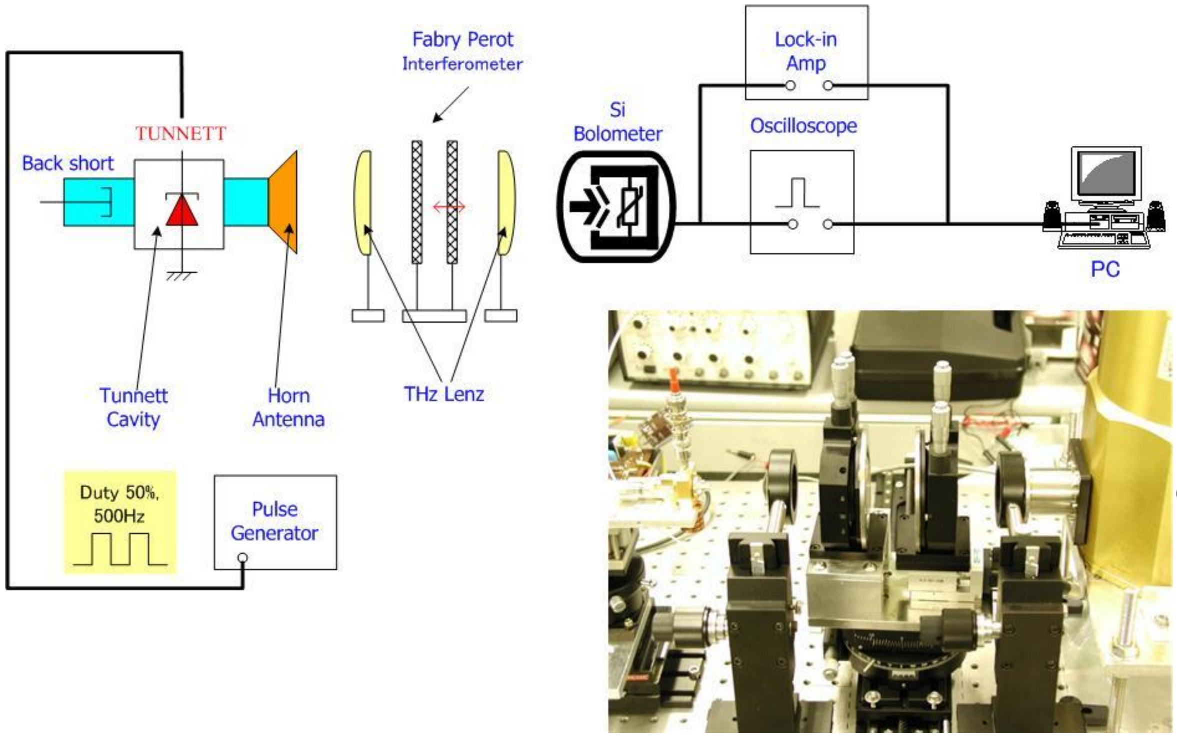




フリーランニングにおける低い位相雑音

$$\begin{aligned} &27\ \text{dB} + 10\log \text{ResBW} \\ &= 27 + 10\log 30000 \\ &= 71.7\ (\text{dB}) \end{aligned}$$

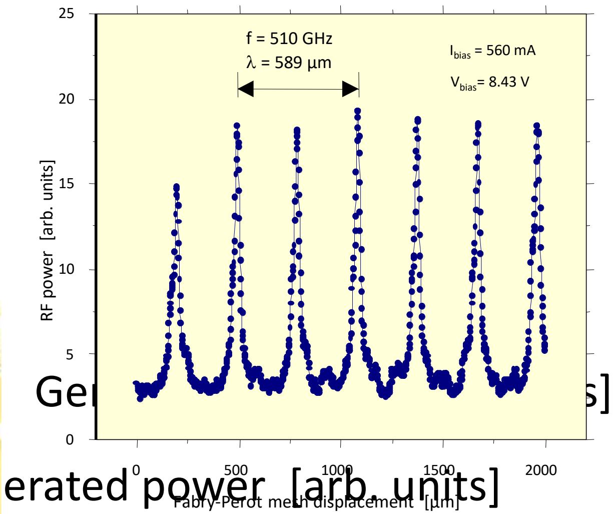
タンネットダイオードの発振スペクトル例(ファブリペロー測定系)

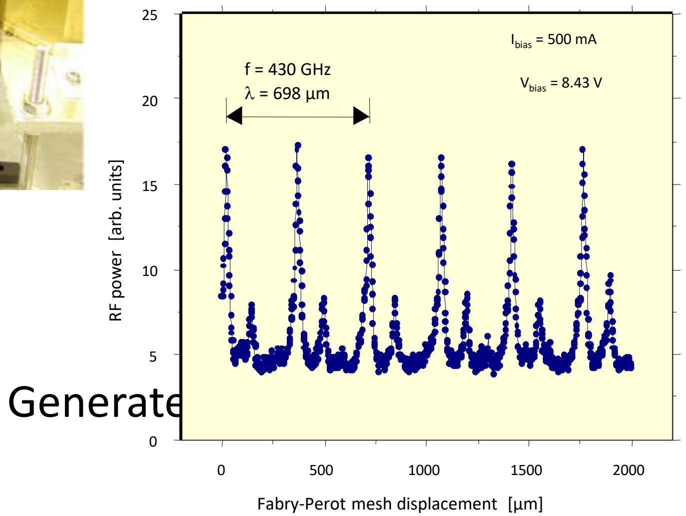


タンネット発振周波数測定システム
（ファブリペロー干渉計システム）

430 - 510 GHz CW, fundamental mode

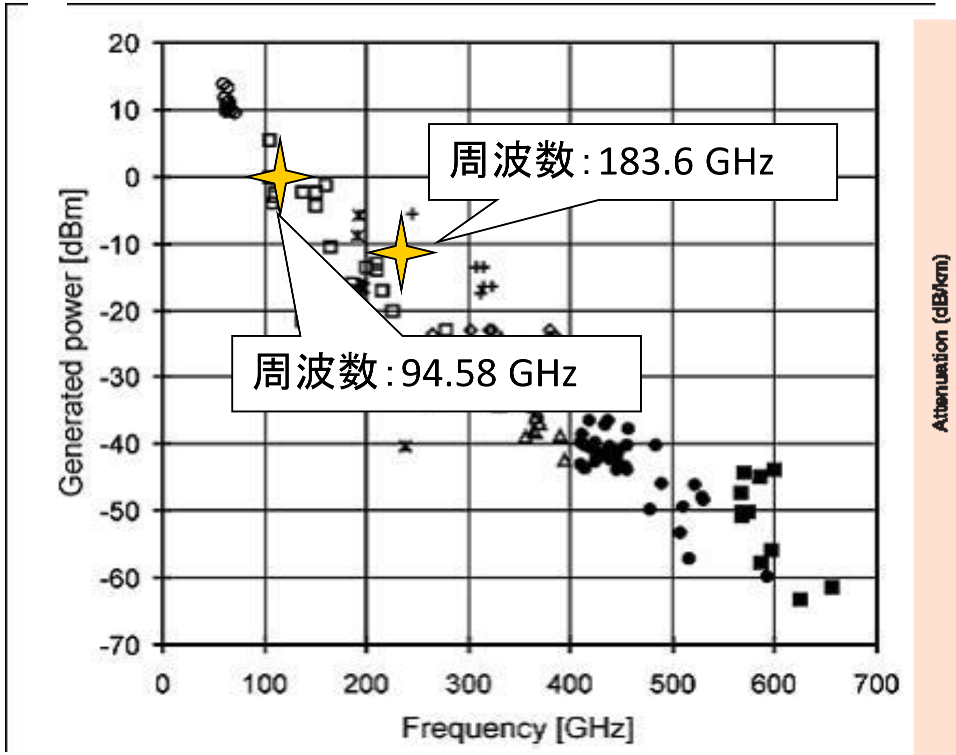
WR-1.5 cavity (0.381 × 0.191 mm)





Application of sub-THz osc devices for imaging

タンネット発振器の周波数選択



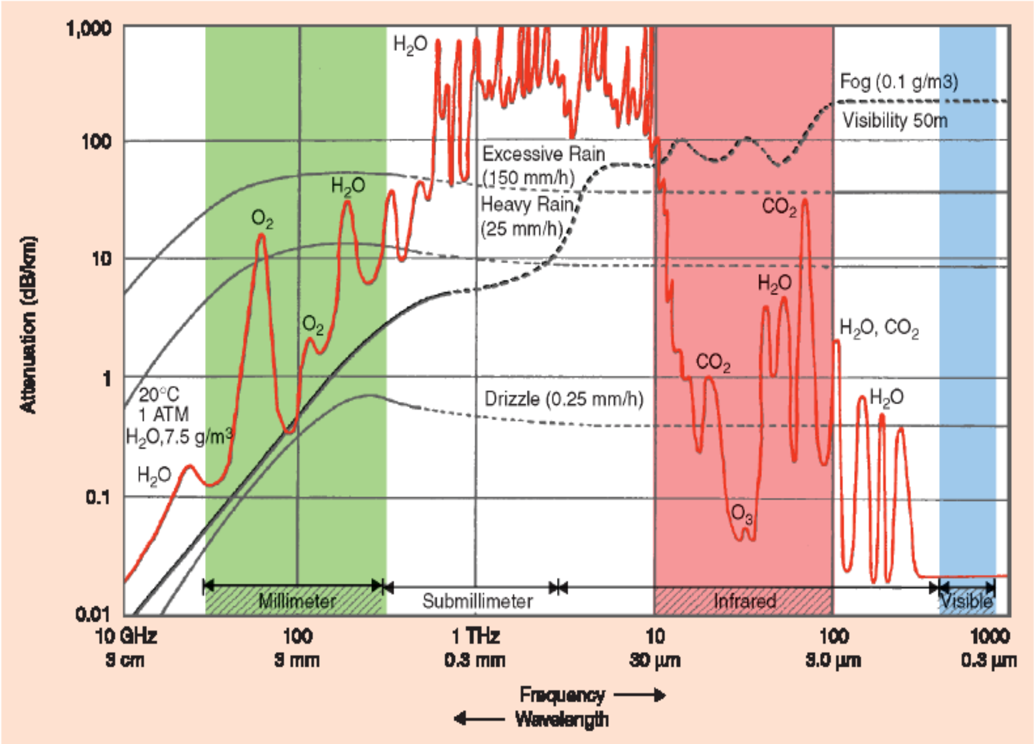


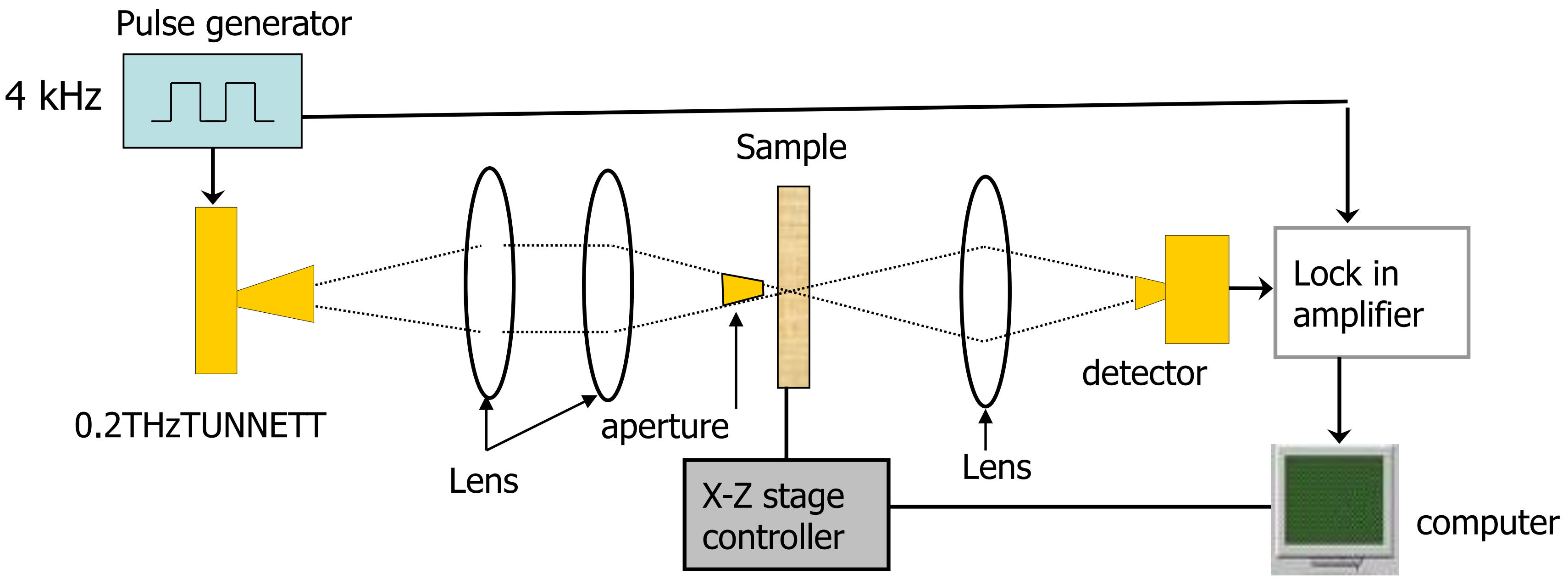
図1 タンネット発振出力の周波数依存性[1]　**図2** 大気および水による電磁波の減衰[2]

Ref. [1]J. Nishizawa, P. Plotka, H. Makabe, and T. Kurabayashi, “GaAs TUNNETT Diodes Oscillating at 430-655 GHz in CW Fundamental Mode”, IEEE microwave and wireless components letters, Vol. 15, No. 9, pp. 597-599, Sep. 2005.

[2] Federal Communications Commission Office of Engineering and Technology New Technology Development Division, Millimeter Wave Propagation: Spectrum Management Implications, No. 70, July,1997

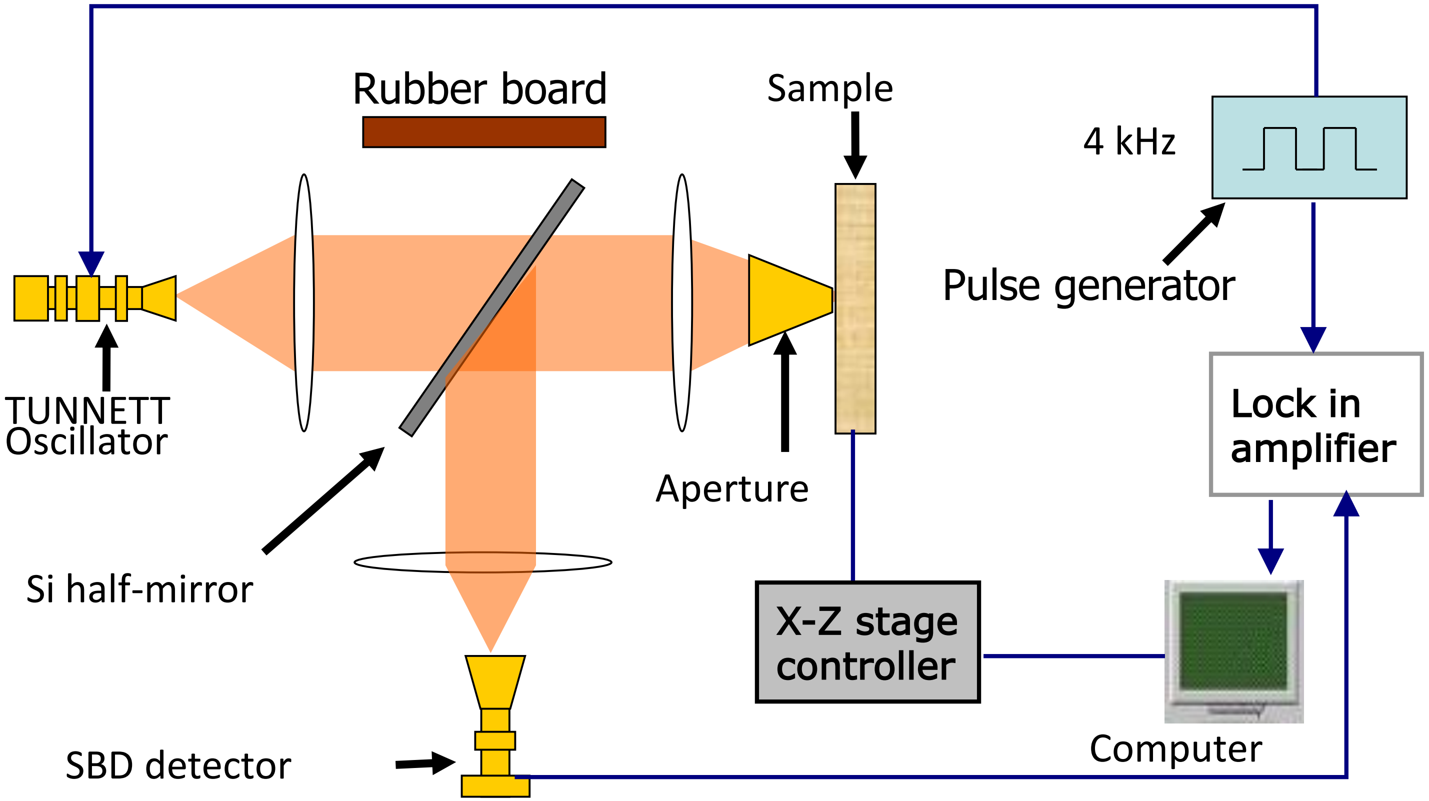
サブテラヘルツイメージング測定装置

- 透過イメージング装置

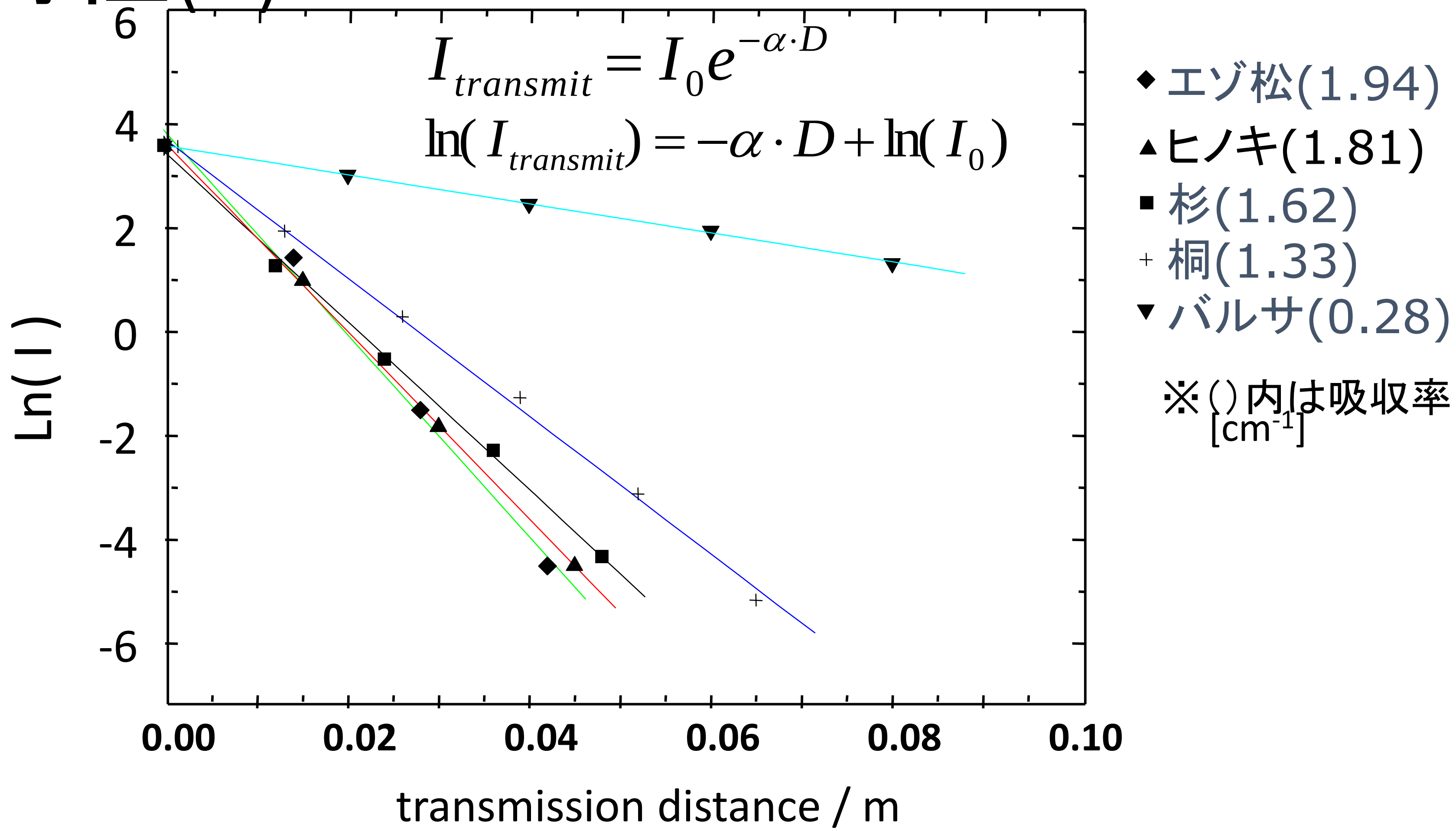


サブテラヘルツイメージング測定装置

- 反射イメージング装置

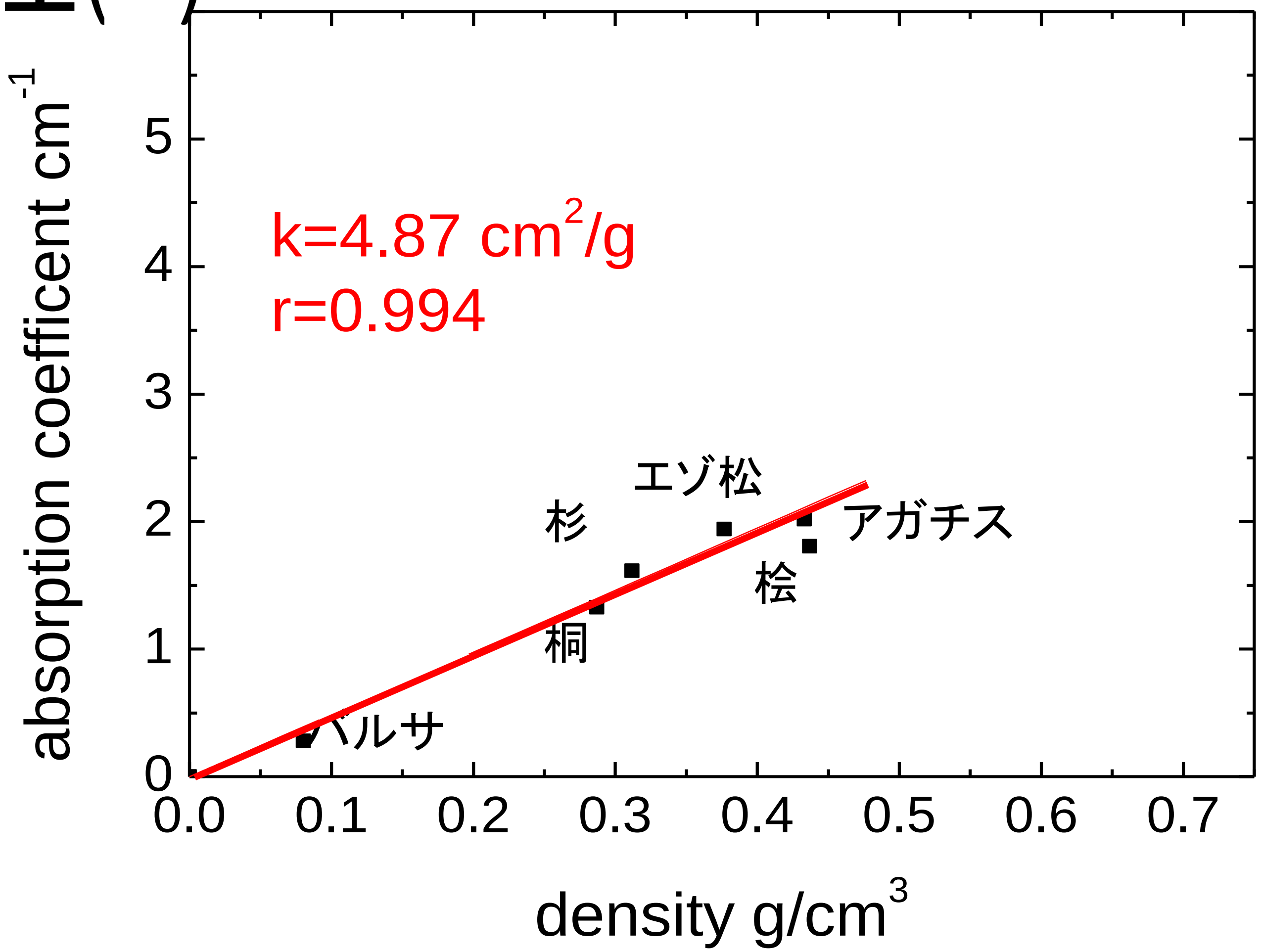


透過特性(1)



強度と透過距離は指数関係

透過特性(2)

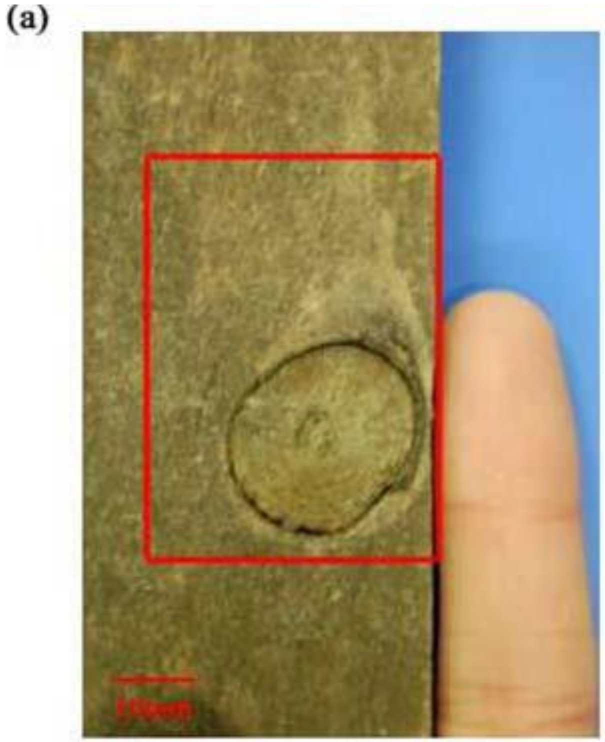


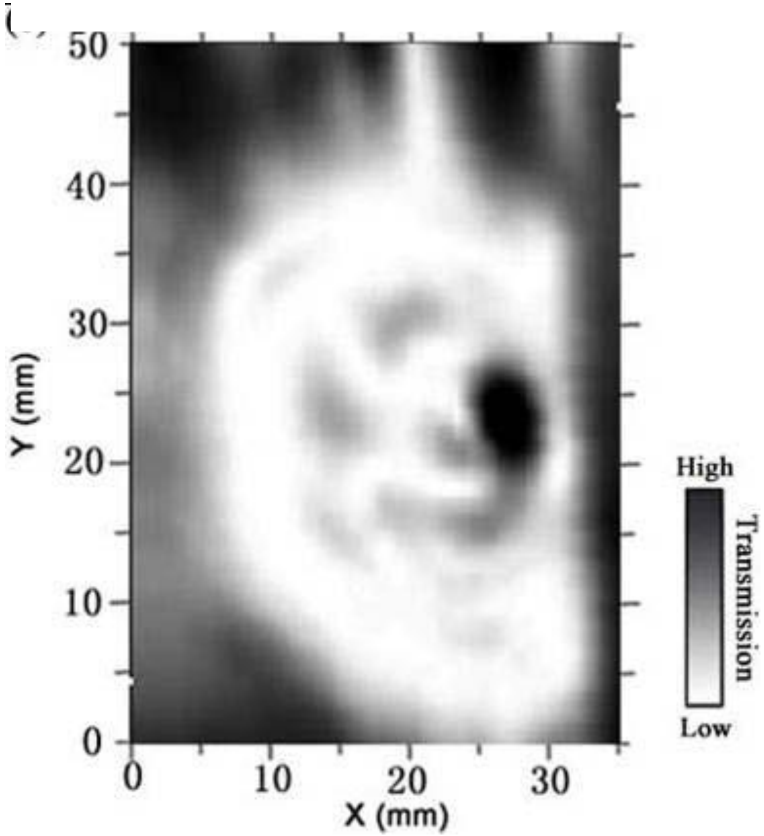
→ 吸収係数と密度は比例関係

不均質構造の透過測定

- 節のイメージング

試料：杉
厚さ：20 mm

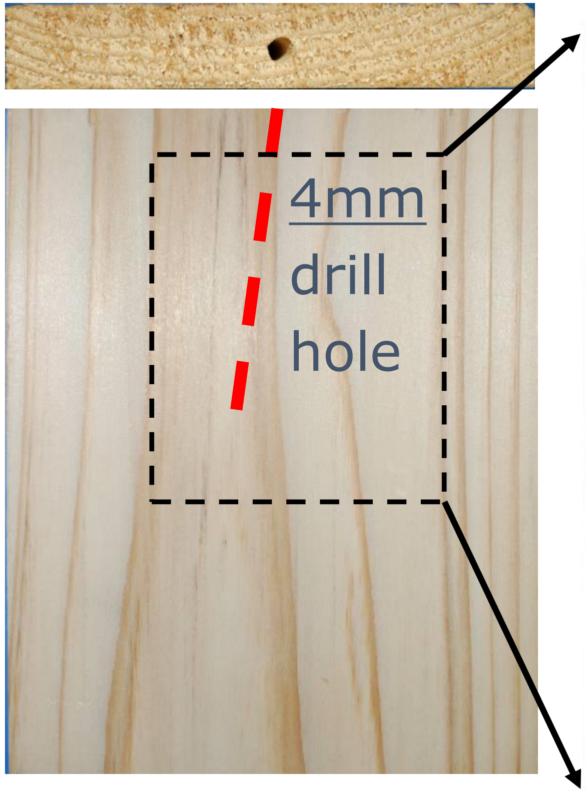


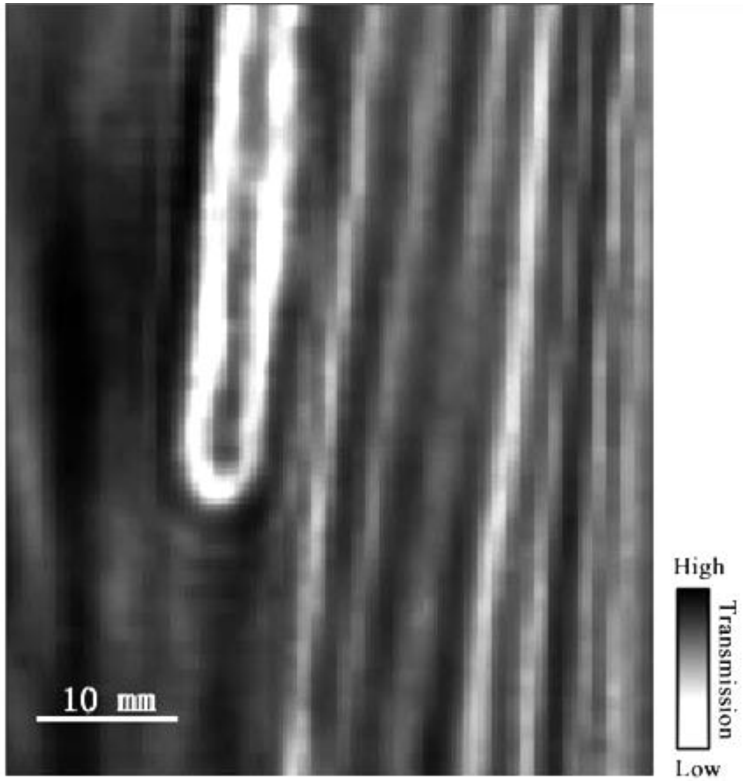


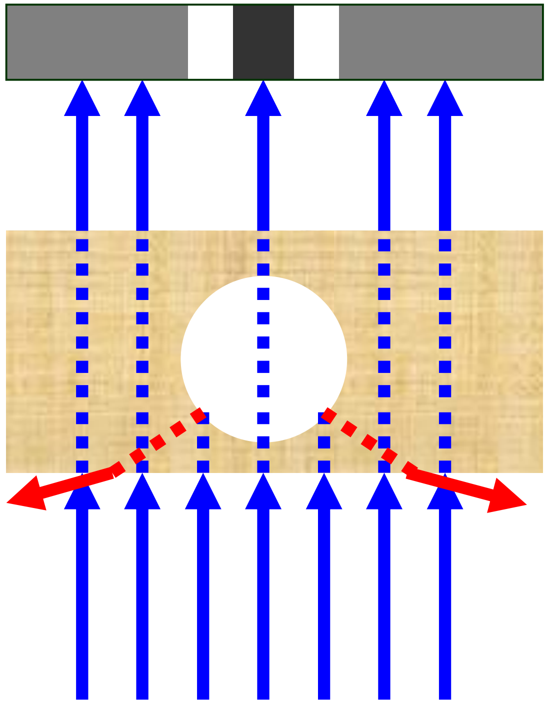
空洞欠陥の透過測定

- 欠陥:ドリル穴

試料:杉
厚さ:12 mm







木材内部への水の浸潤－透過測定

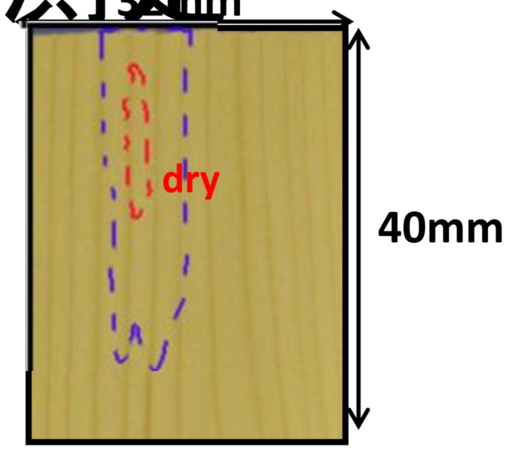
- 欠陥：過剰水分（浸潤測定）

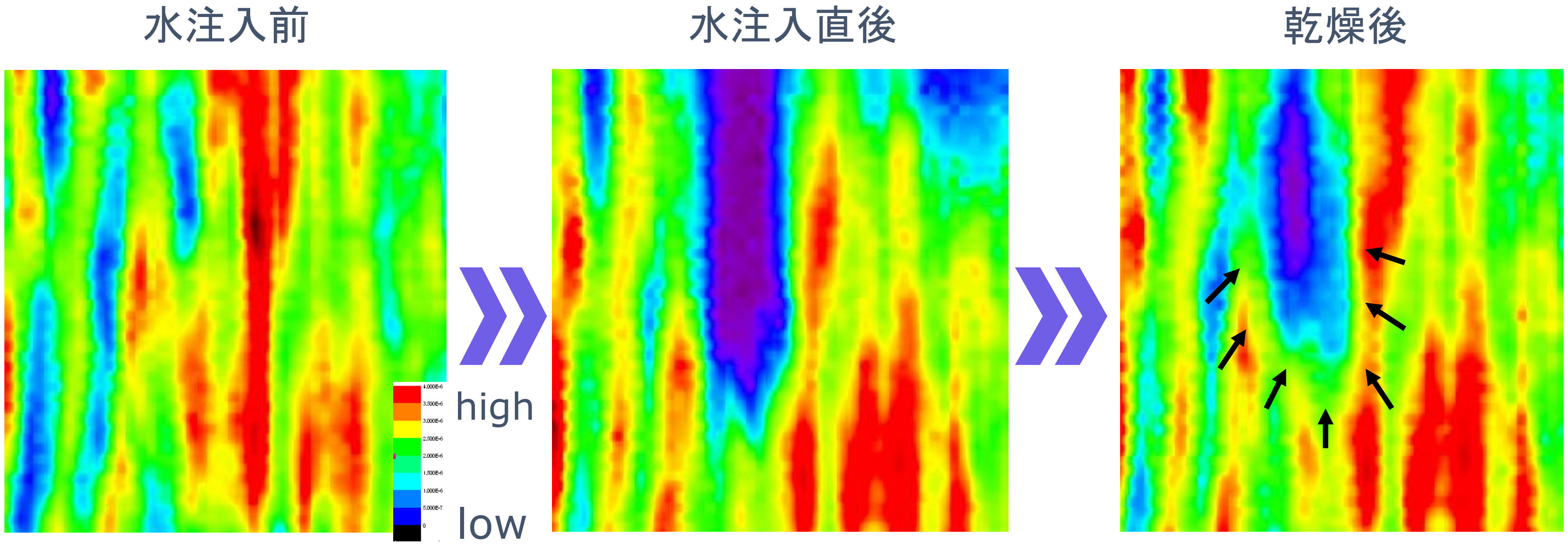
試料に注射器で水を注入した後、水分の広がりを透過測定で観察する

⬇

水も透過してしまうX線では困難

試料：トウヒ
厚さ：14.2 mm





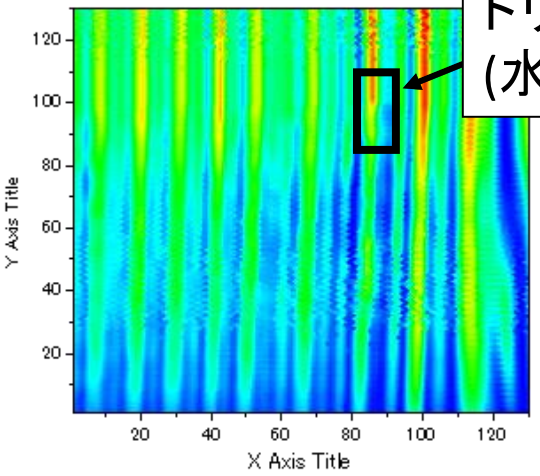
木材内部への水の浸潤ー反射測定

試料：杉
厚さ：12 mm

ドリル穴(5 mm径)に水を注入

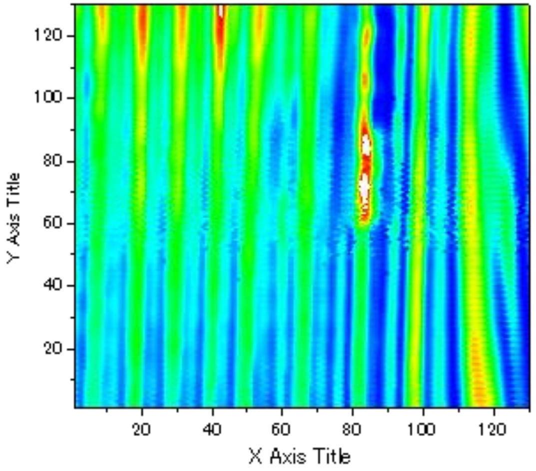
反射測定

水注入前

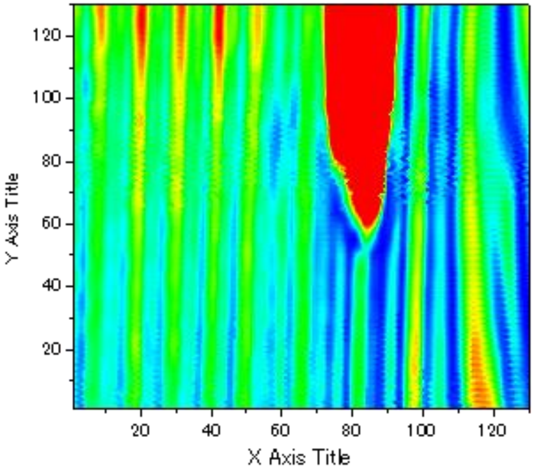


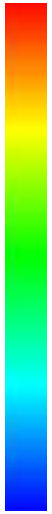
ドリル穴
(水注入領域)

水200 ml



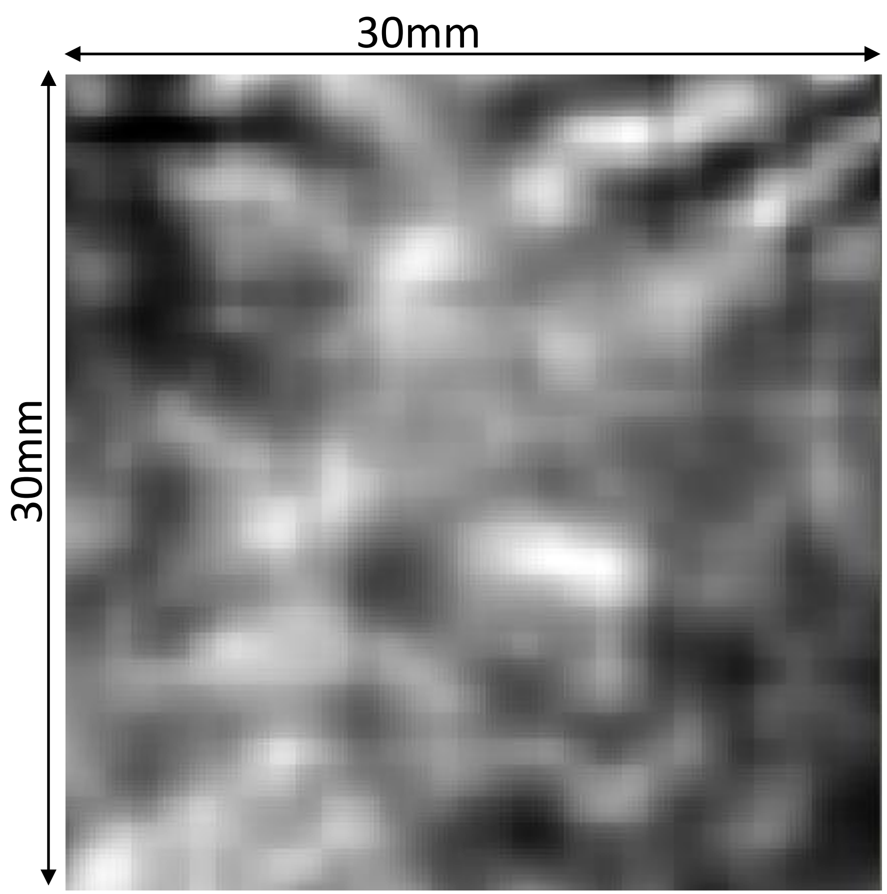
水400 ml



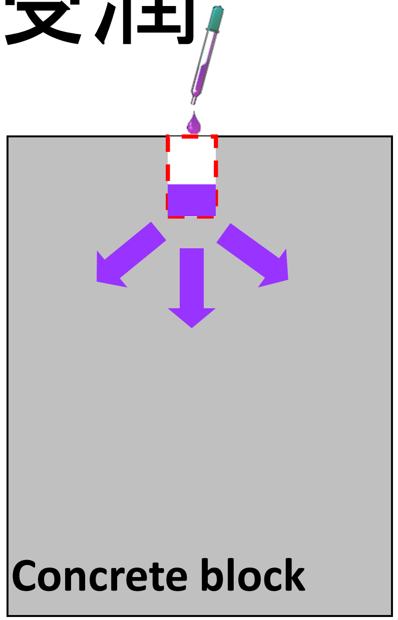


大
反射強度
小

コンクリート内部への水の浸潤

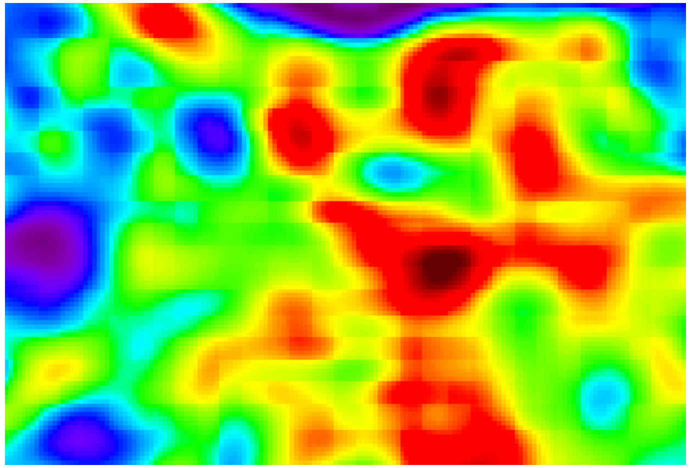


コンクリート(厚さ10mm)内部における
水の浸潤の様子(透過測定)

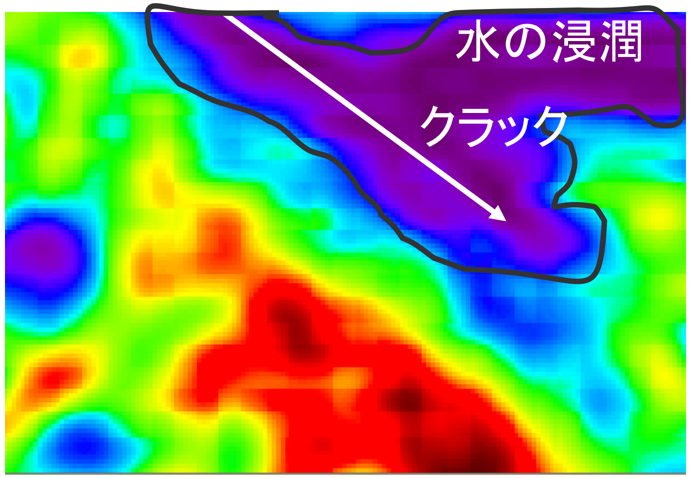


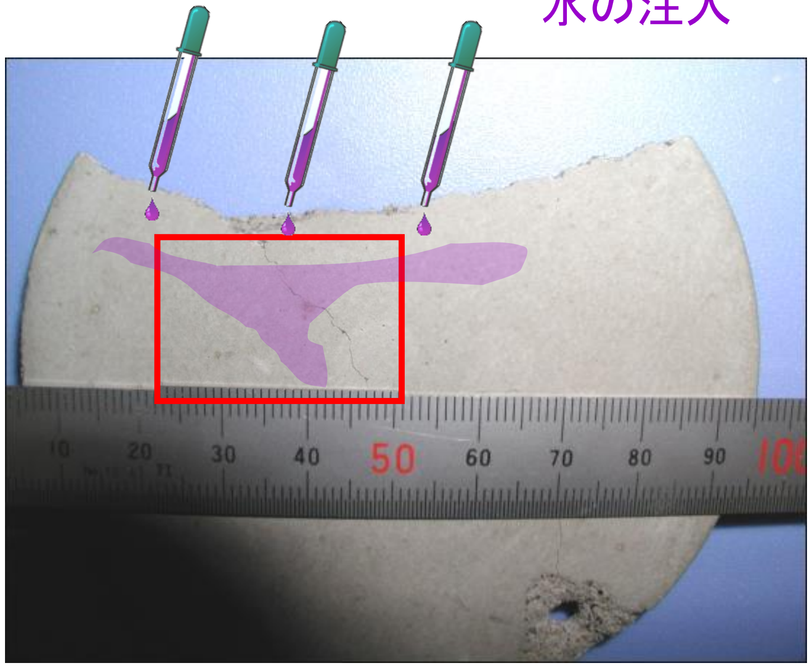
クラックの透過測定

水注入前



水注入後



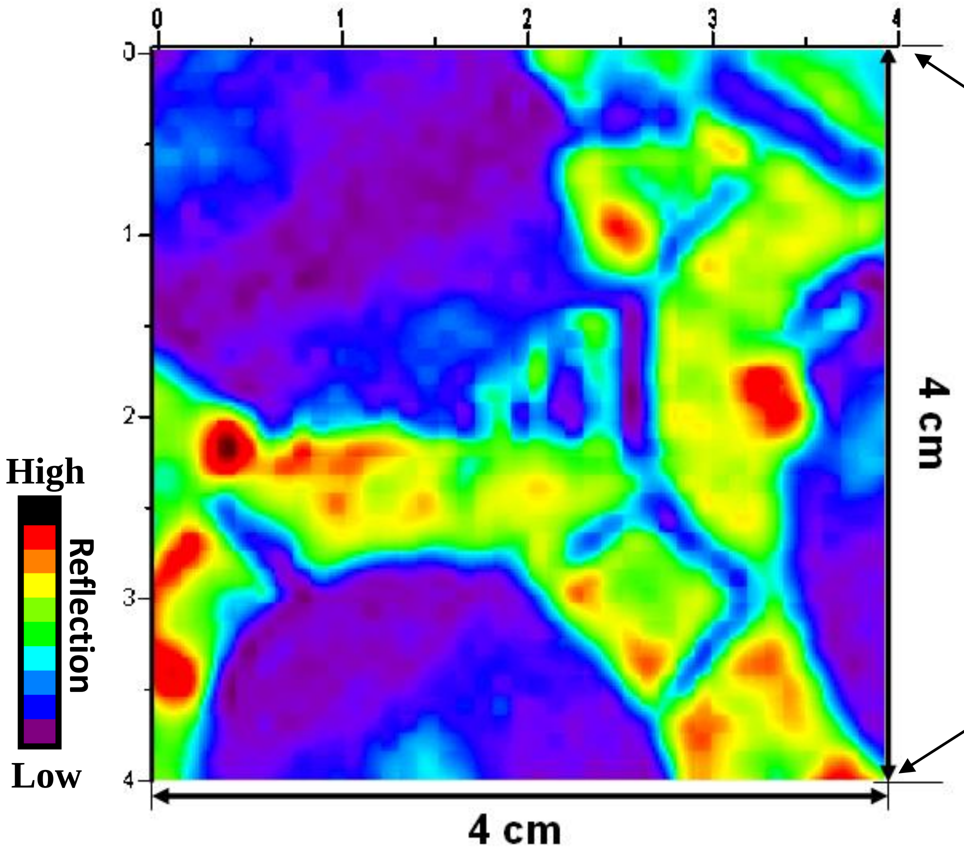


クラック周辺の水によるテラヘルツ波の吸収

↓

クラック検出の手がかり

セラミックタイルの接着不良欠陥



反射測定におけるセラミックタイルのイメージング画像