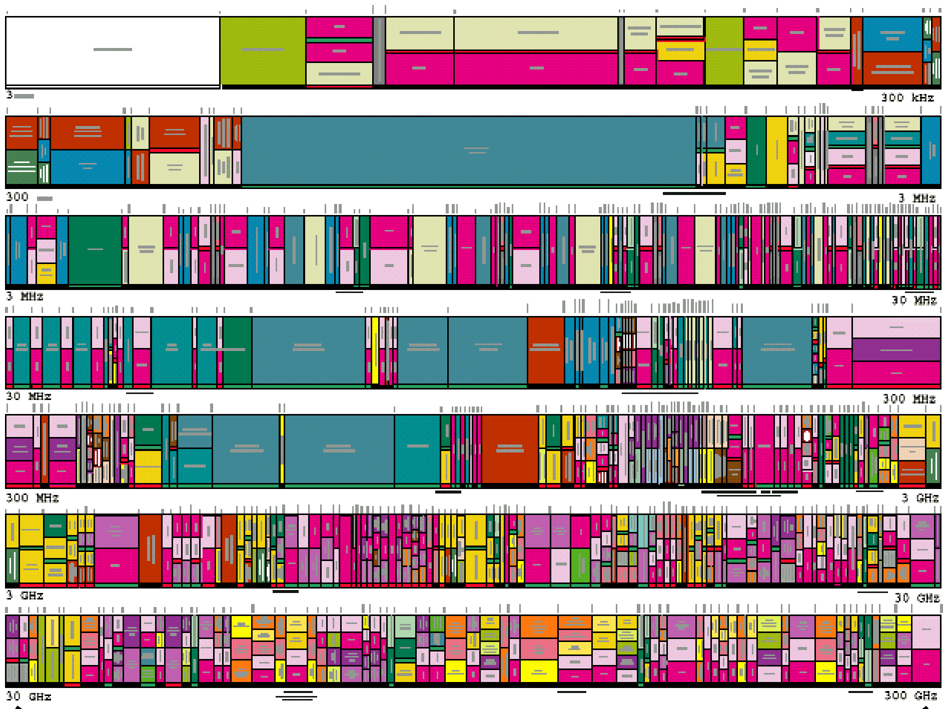
Materials Science in Electronics devices
- Semiconductor devices -

2016 Yutaka Oyama
oyama@material.tohoku.ac.jp
http://www.material.tohoku.ac.jp/~denko/lab.html

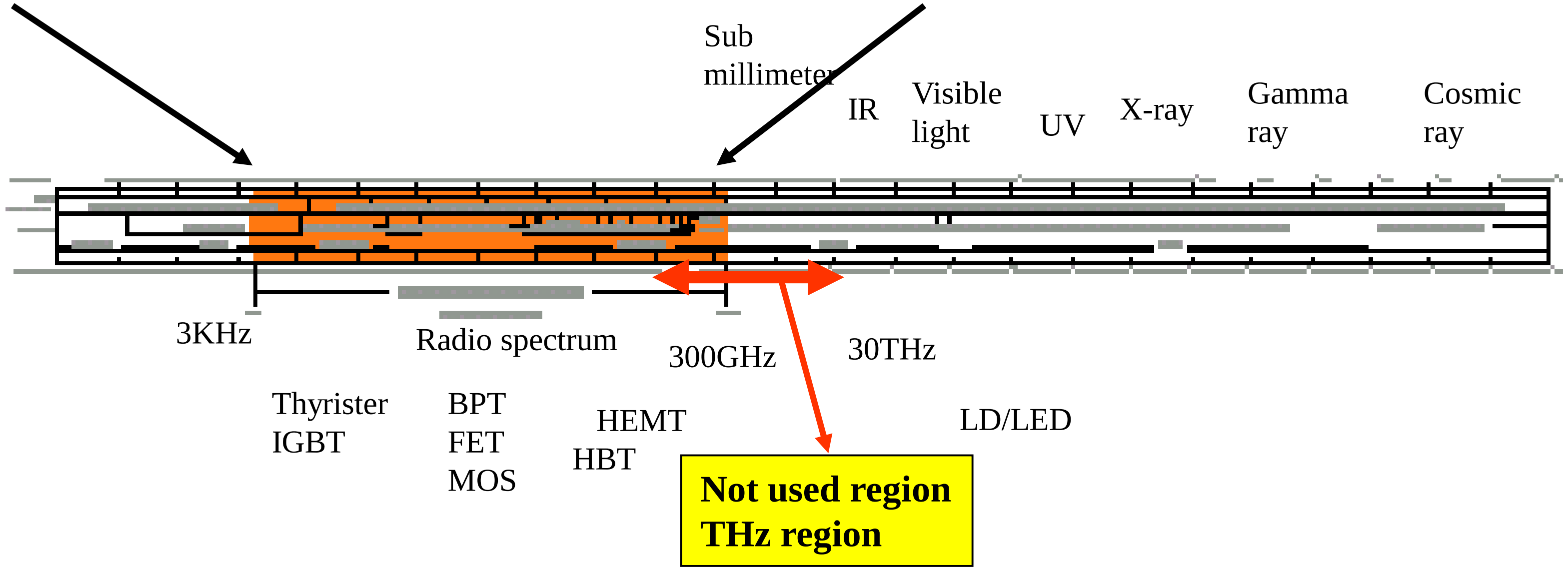
Contents

Frequency Allocation (USA)



Our target device for not-used THz region

ISIT
TUNNETT
(Semiconductor Raman laser) -30THz



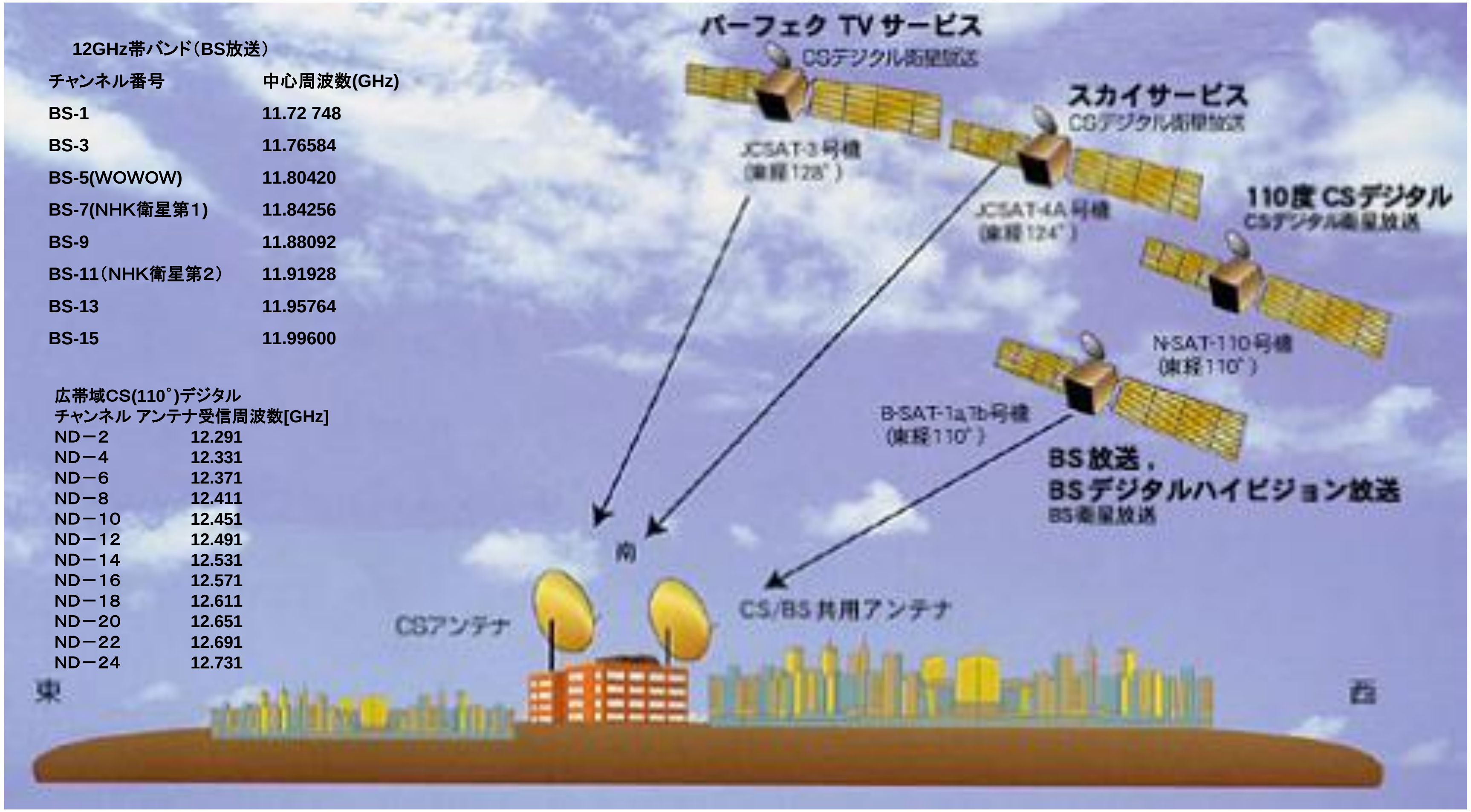
BS,CS bands from satellite to the earth

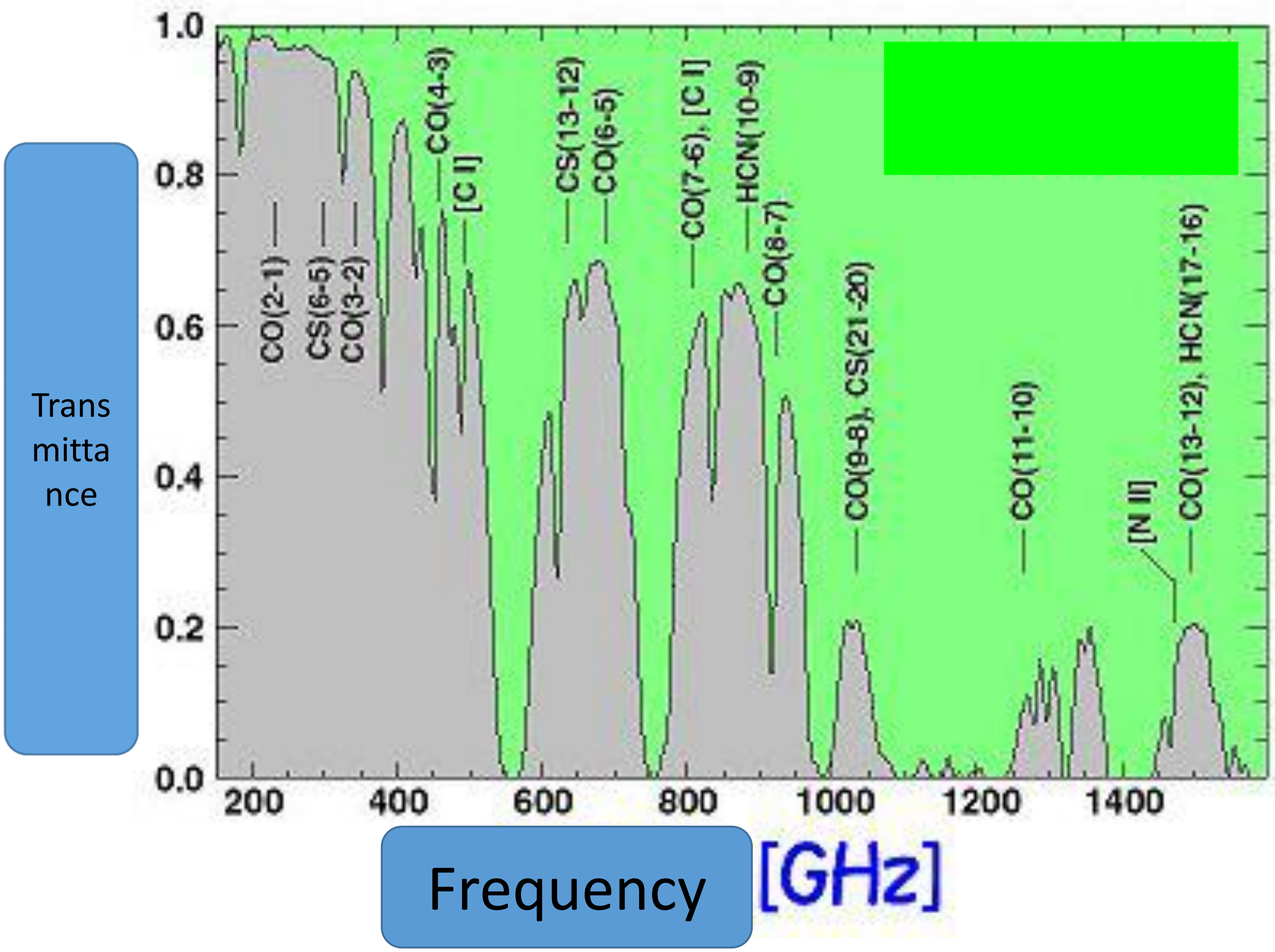
12GHz帯バンド（BS放送）

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

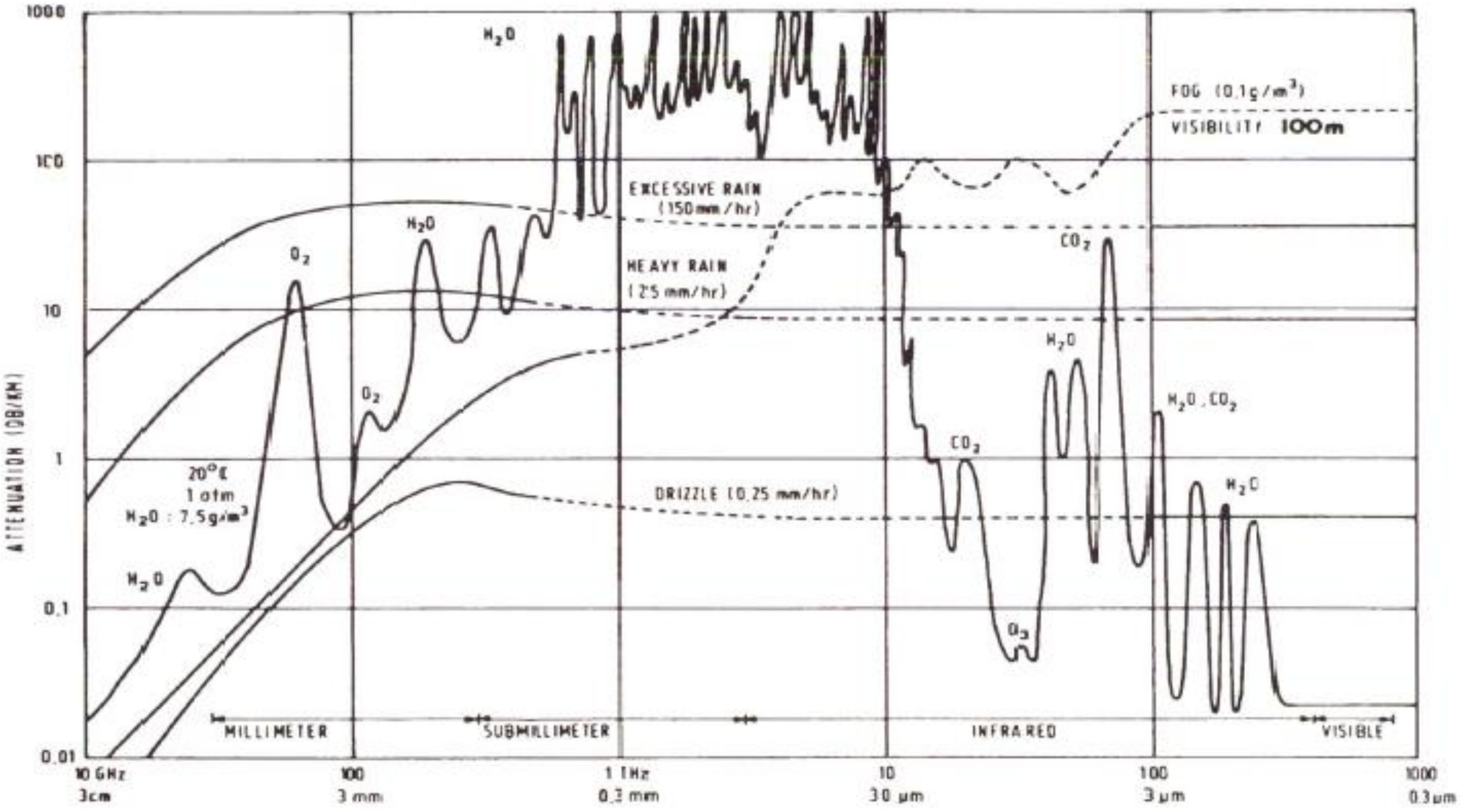
チャンネル	アンテナ受信周波数[GHz]
ND－2	12.291
ND－4	12.331
ND－6	12.371
ND－8	12.411
ND－10	12.451
ND－12	12.491
ND－14	12.531
ND－16	12.571
ND－18	12.611
ND－20	12.651
ND－22	12.691
ND－24	12.731





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]

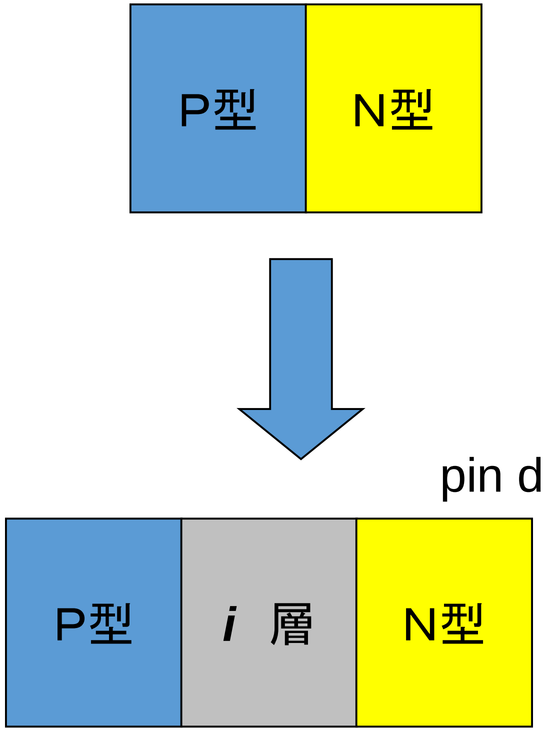
Detailed attenuation characteristics in Air



pin diode

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

pn diode



pin diode

高抵抗
高純度*i*層

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

Carrier recombination in *i*-layer

Fast operation

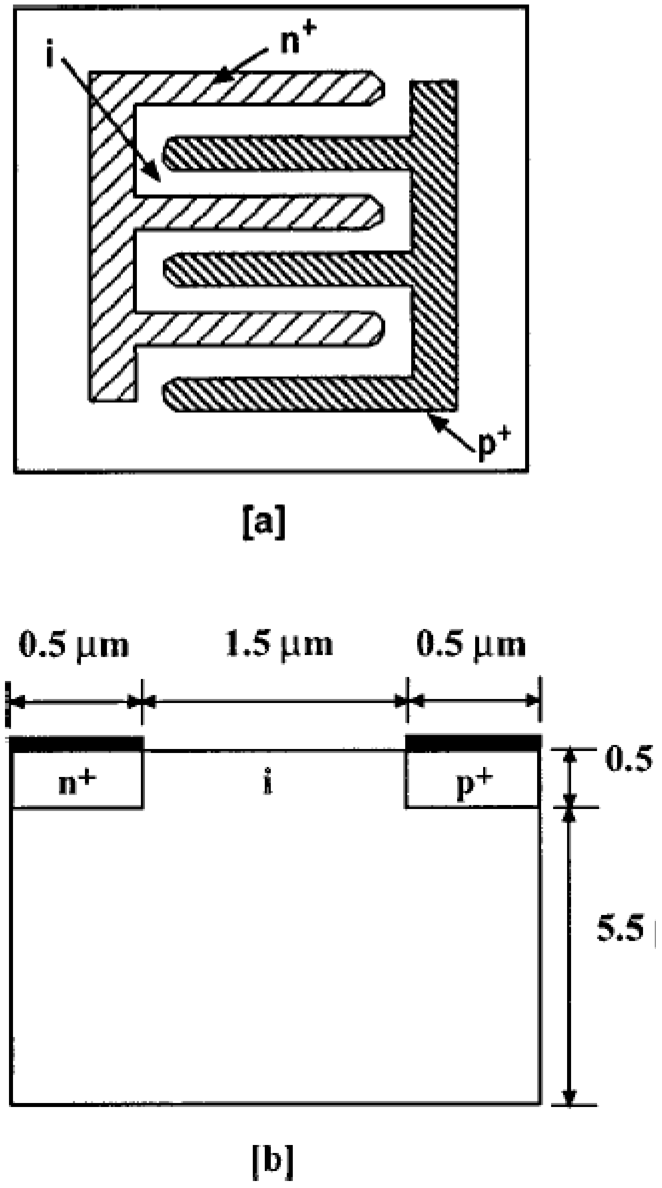
Insertion of high purity *i*-layer

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



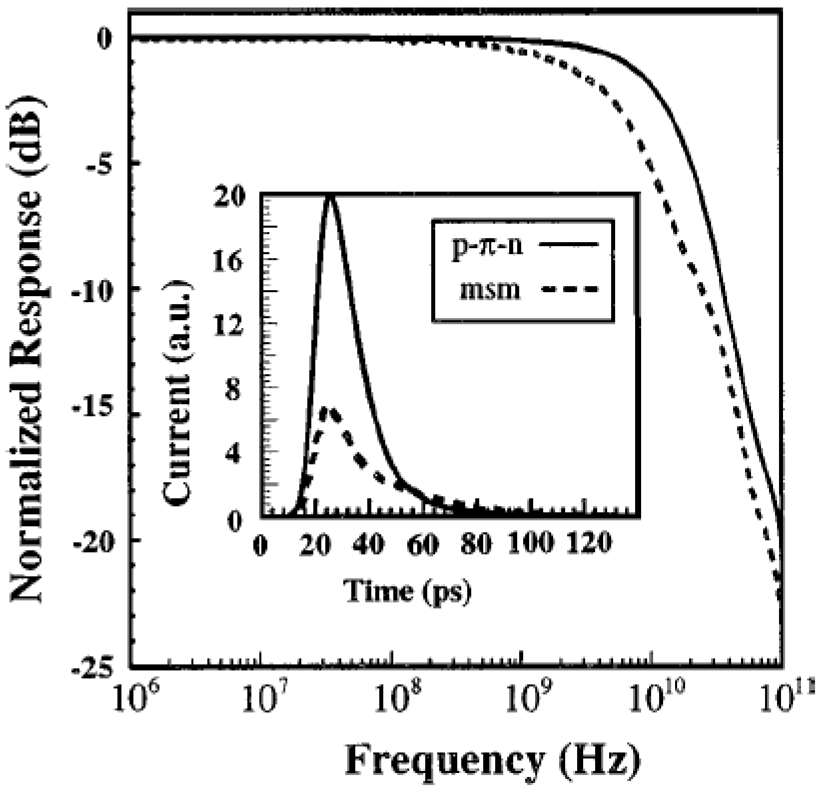
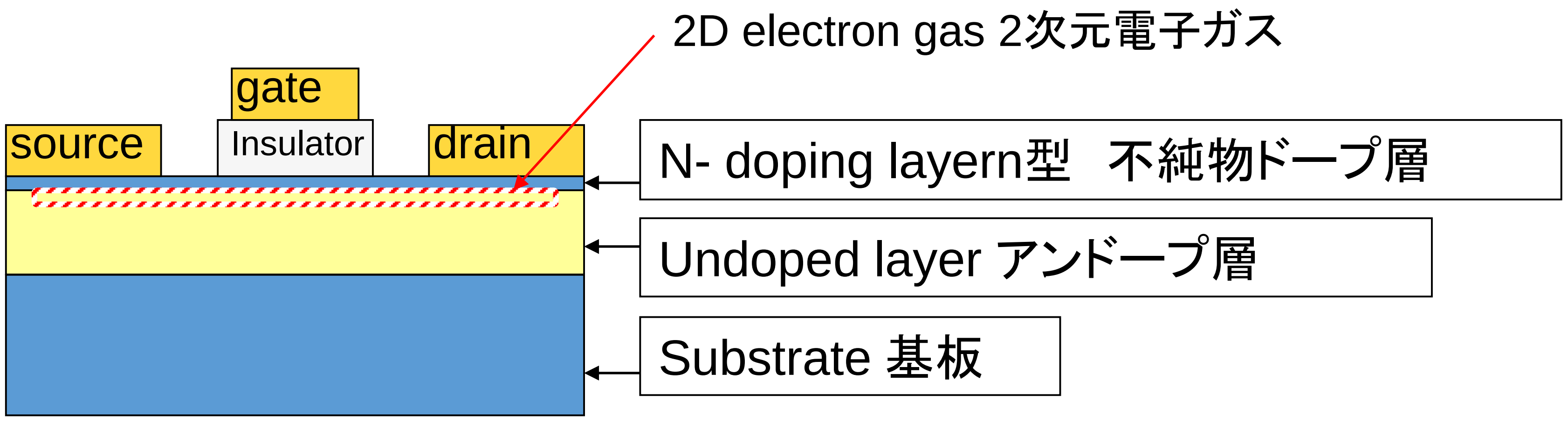


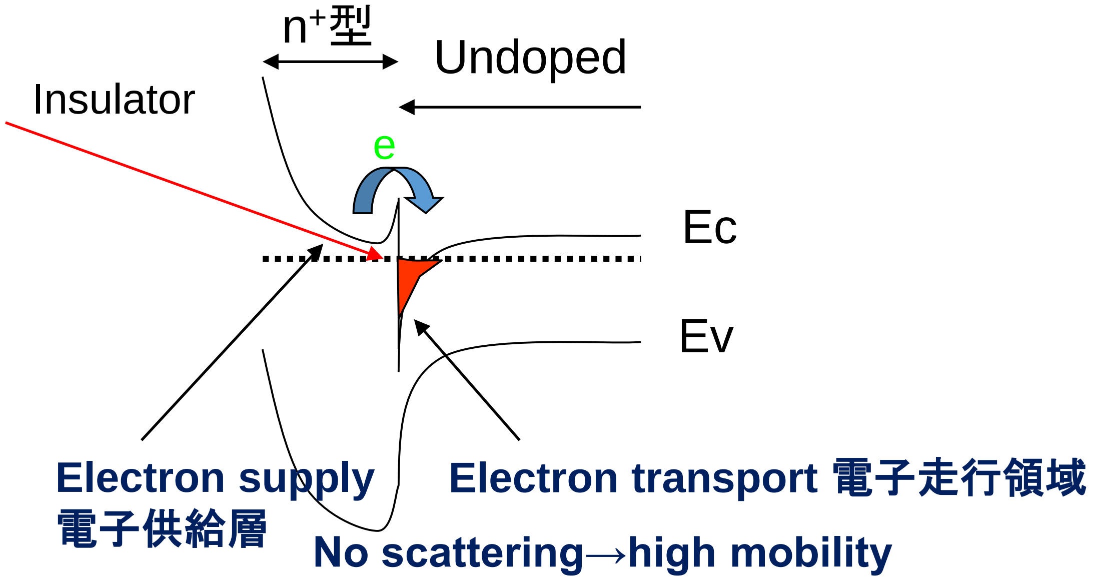
FIG. 2. Calculated frequency response in dB for the p-π-n LPIN and MSM photodetectors shown in Fig. 1. The inset shows the temporal response of the photodetectors showing the higher responsivities of the p-π-n structure compared to the MSM device.

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



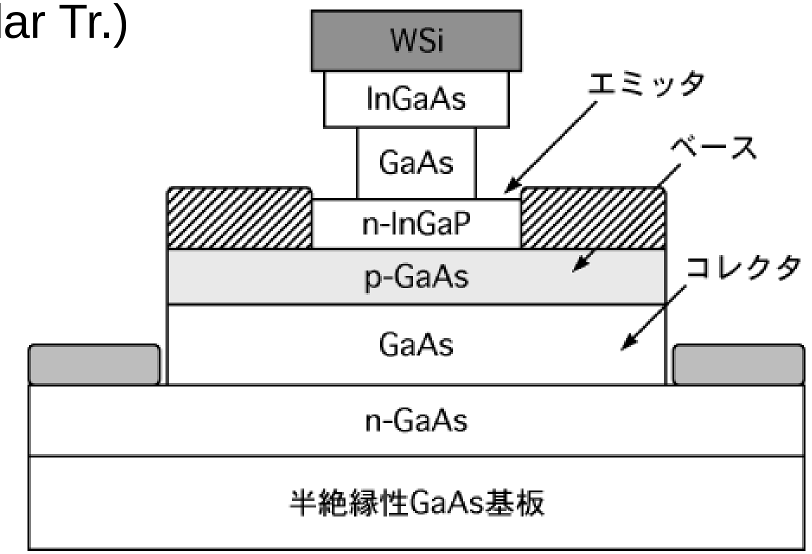
Mechanism for high conductance
Carrier supply & carrier transport
⇒
Achievement of high carrier concentration &
High carrier mobility



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

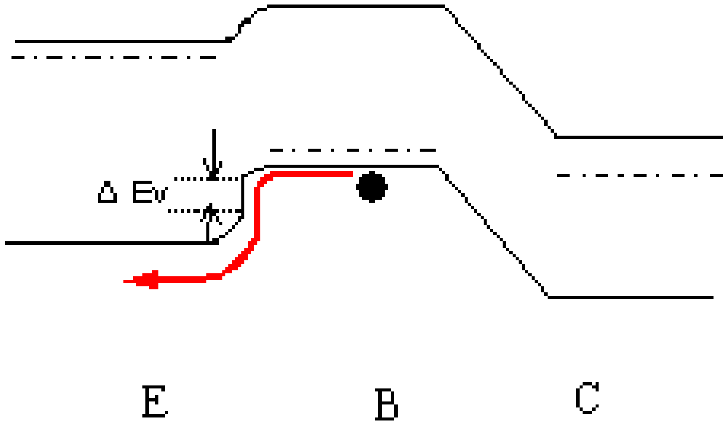


エミッター接地回路の**電流利得** β は、ベース電流に対するコレクター電流の比ですから、

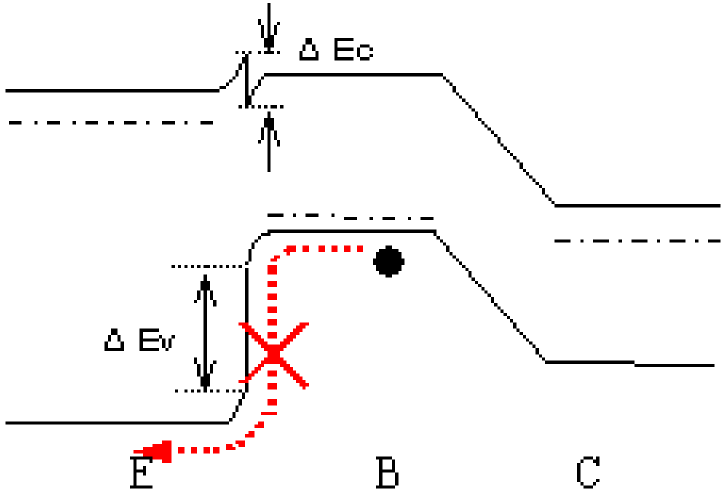
$$\beta = \frac{\partial I_C}{\partial I_B} = \frac{\alpha}{1-\alpha}$$

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

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



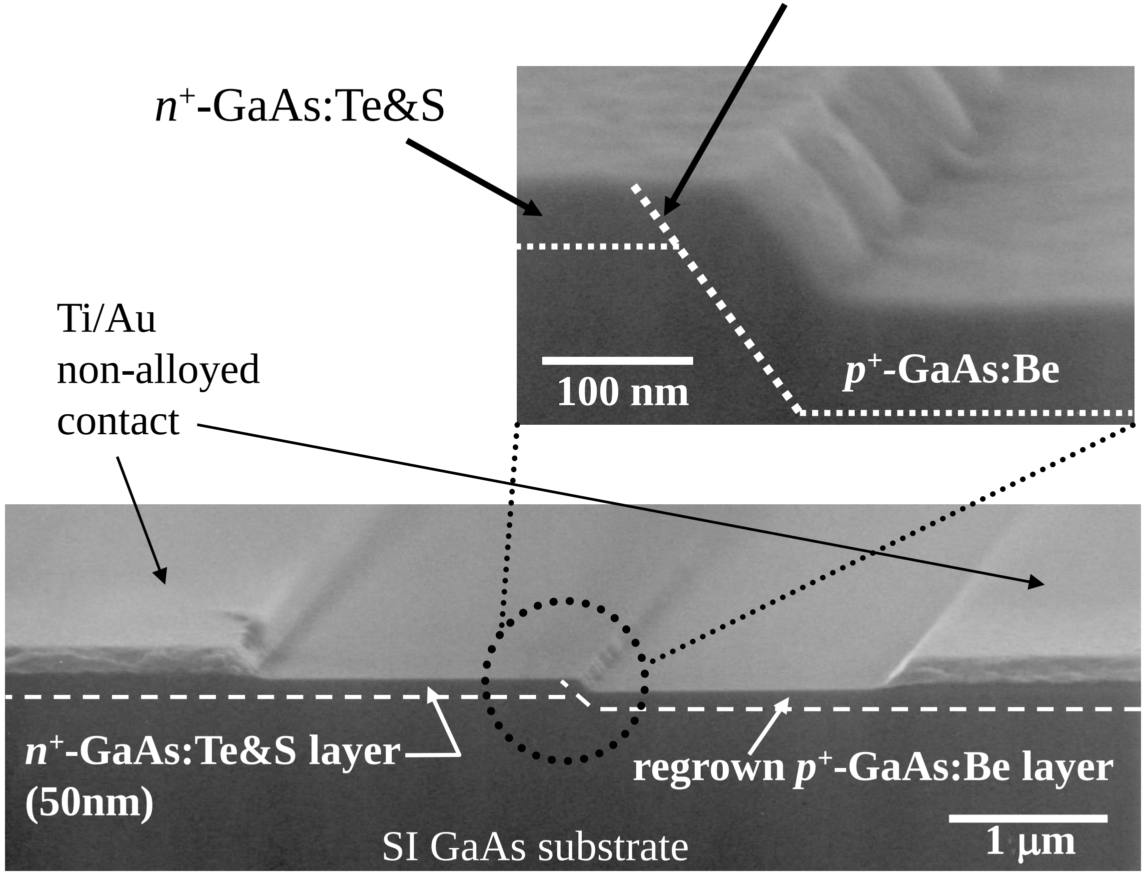
Conventional bipolar Tr.



Hetero bipolar Tr.

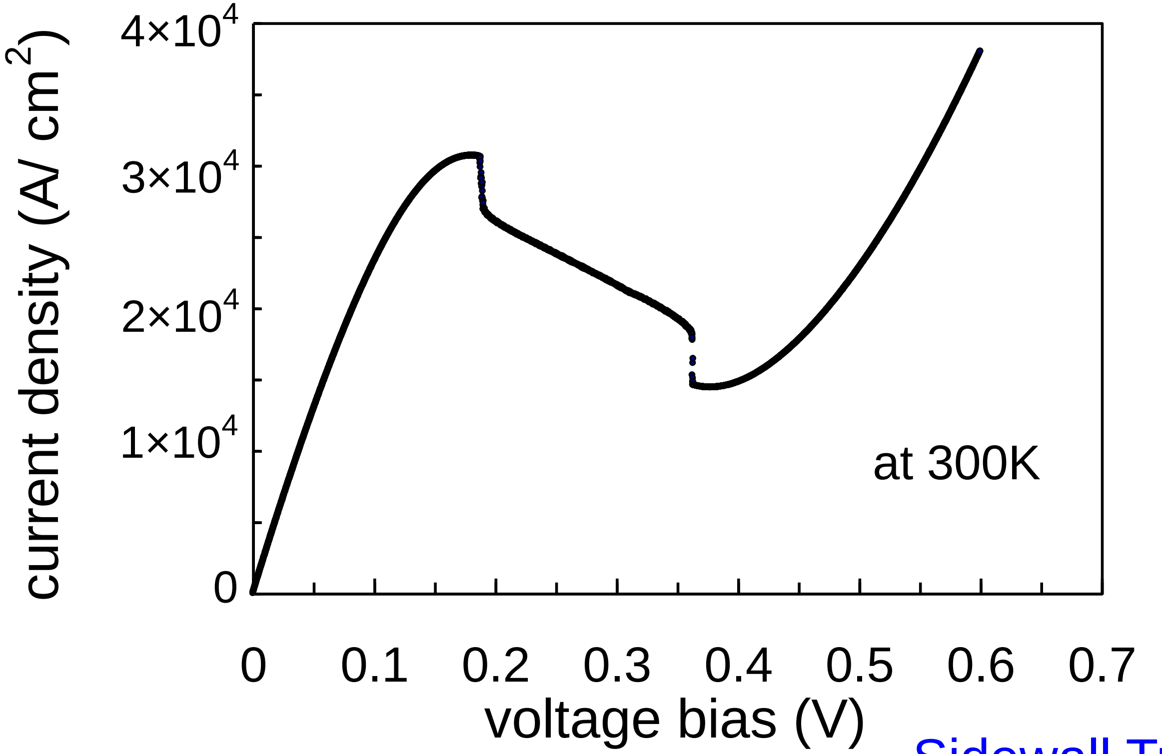
高性能p^+n^+トンネルダイオード

High performance
Regrown p^+n^+ tunnel junction



高性能p^+n^+ダイオード

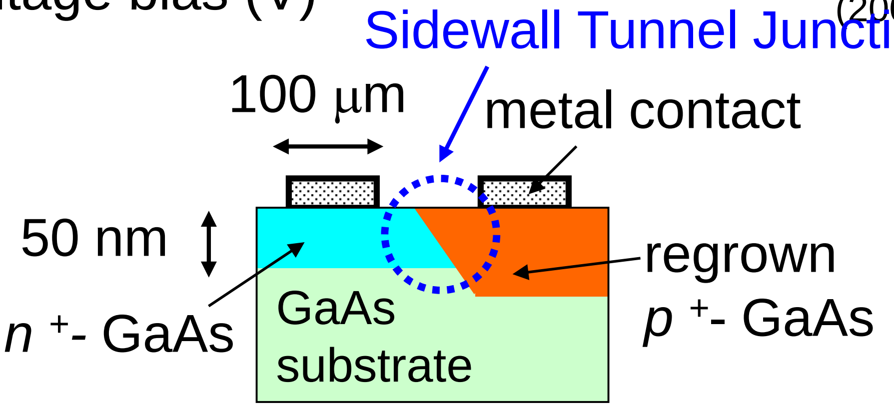
High performance
Regrown $p^+ n^+$ tunnel junction



peak current density (J_p)
MAX. 31000 A/ cm^2
peak-to-valley current ratio
2.1

previous 1800 A/ cm^2
RECORD J_p
17 times higher

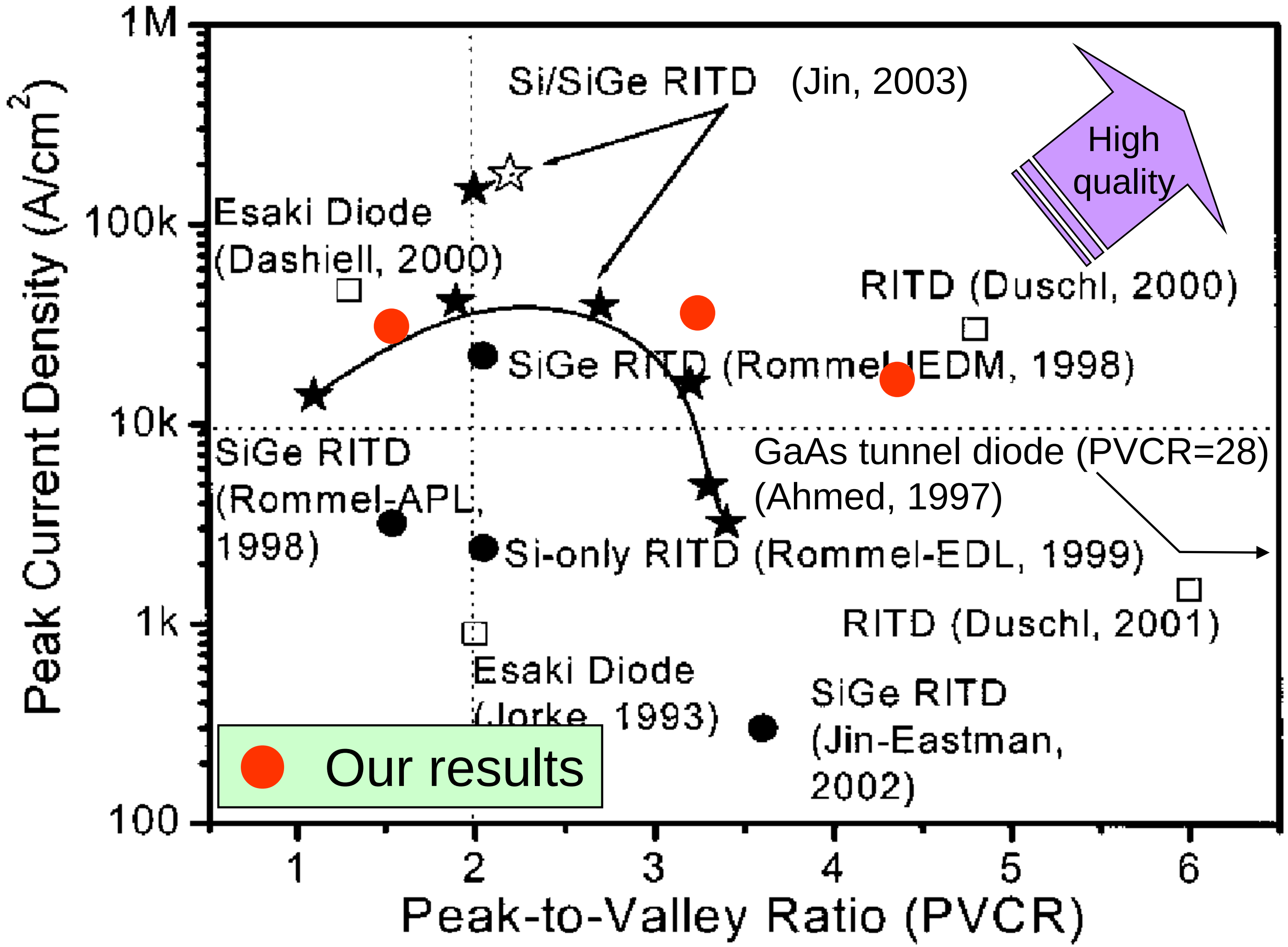
reference:
Y. Oyama *et al.*,
Appl. Phys. Lett., **81**(14),
(2002), pp. 2563-2565.



GaAs:Te&S
360℃成長
n^+ =1.5x10^{19} cm^{-3}

GaAs:Be
290℃再成長
p^+ =8x10^{19} cm^{-3}

高性能p^+n^+ダイオード



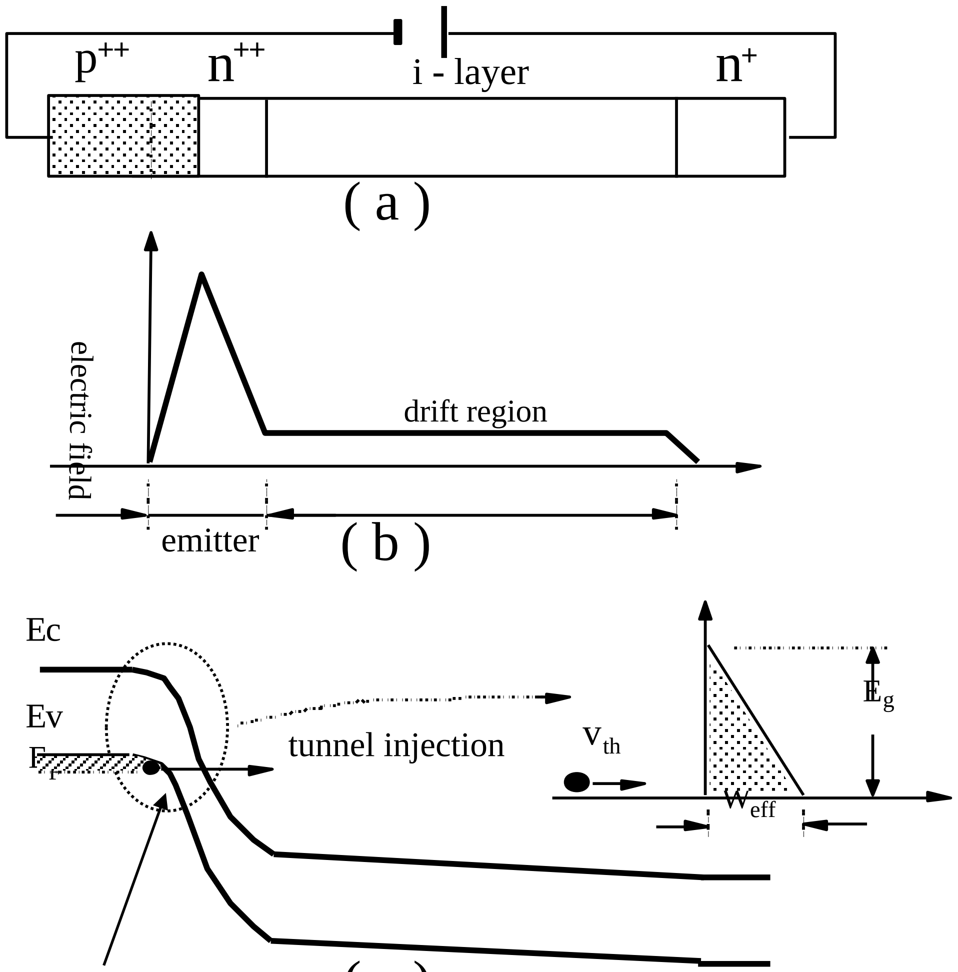
1M
100k
10k
1k
100
Peak Current Density (A/cm²)
1
2
3
4
5
6
Peak-to-Valley Ratio (PVCR)
Si/SiGe RITD (Jin, 2003)
High quality
Esaki Diode (Dashiell, 2000)
RITD (Duschl, 2000)
SiGe RITD (Rommel-IEDM, 1998)
SiGe RITD (Rommel-APL, 1998)
GaAs tunnel diode (PVCR=28) (Ahmed, 1997)
Si-only RITD (Rommel-EDL, 1999)
RITD (Duschl, 2001)
Esaki Diode (Jorke, 1993)
SiGe RITD (Jin-Eastman, 2002)
Our results

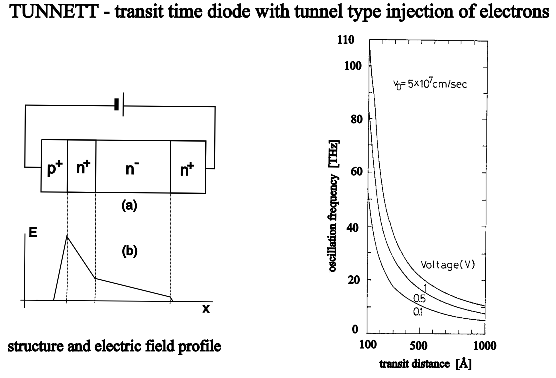
PRINCIPLE OF TUNNETT DIODE

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





structure and electric field profile

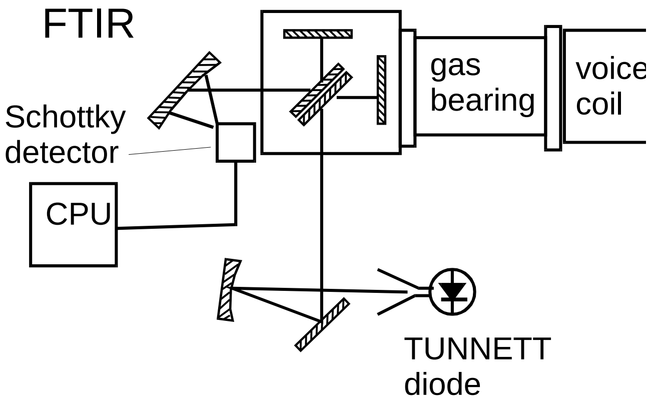
expected performance with ballistic mode transport in transit region

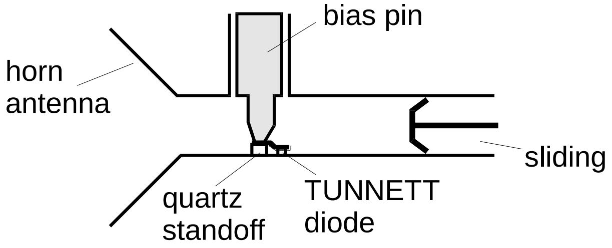
$p^{+}n^{+}$ tunnel injection layer requires
Very thin (nm) n^{+} layer with atomic accuracy
with very steep impurity profile

Application of MLE

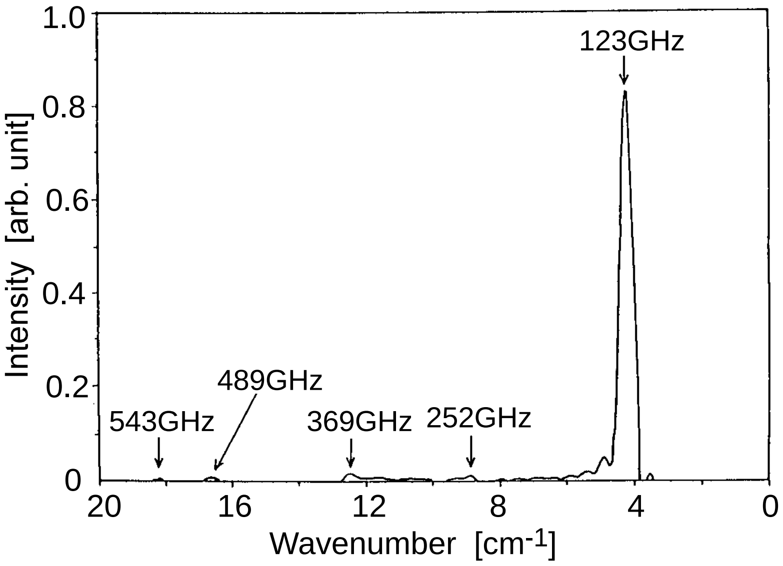
●*Performance in brief*
✧*TUNNETT*

TUNNETT oscillation measured with FTIR





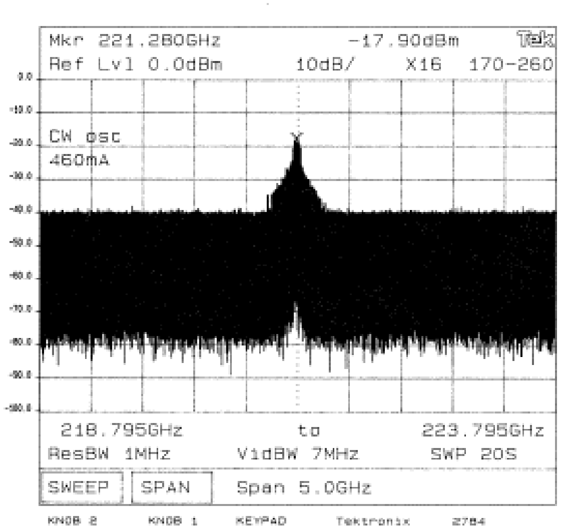
TUNNETT oscillator in a waveguide cavity coupled to a horn antenna

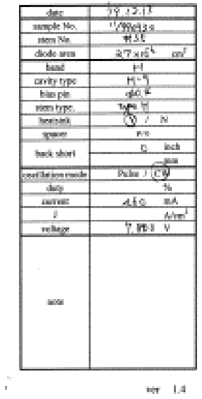


oscillation spectra

●*Performance in brief*

✧*TUNNETT*





Tunnett oscillation sheet

221 GHz, MLE wafer, H-band cavity

Phase noise
-70dBc/Hz
(1KHz)

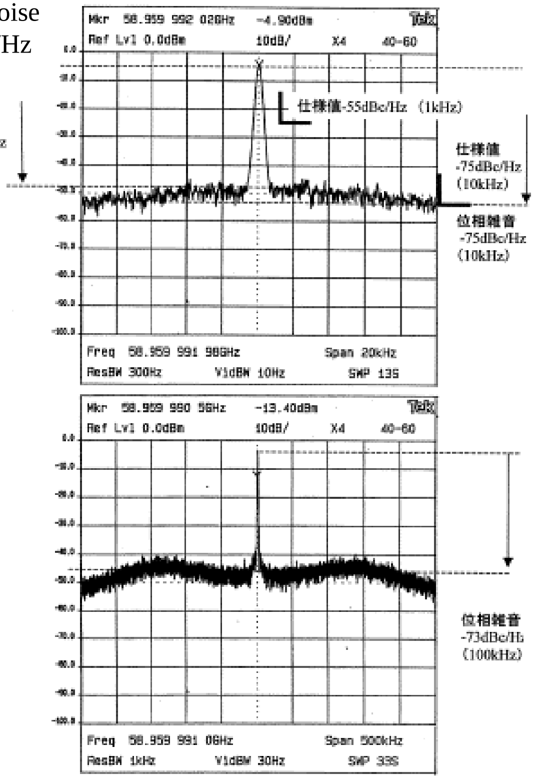
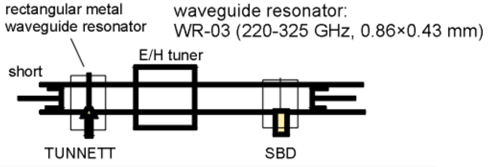


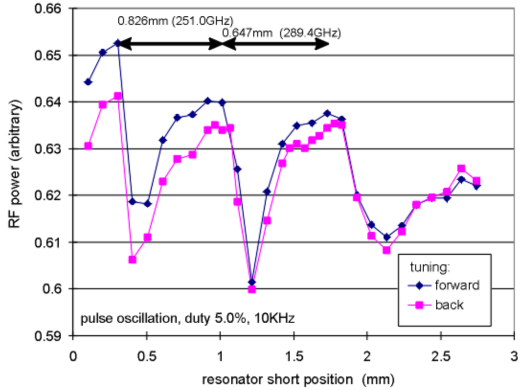
図2 58.96GHz 発振器位相雑音特性

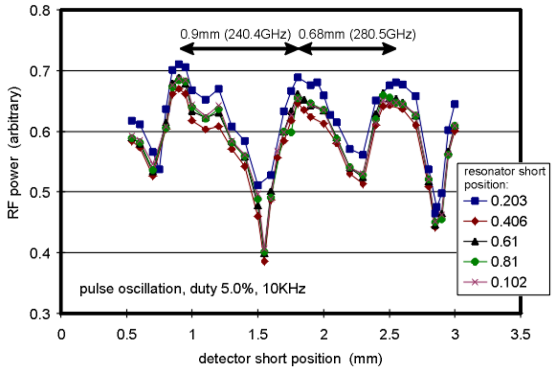
Phase noise
-73dBc/Hz
(100KHz)

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

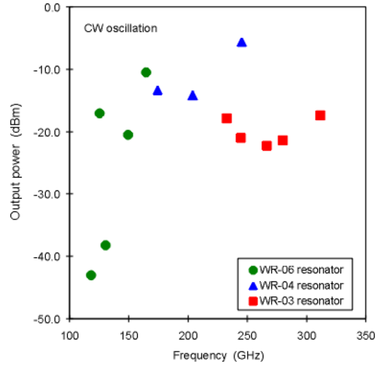
TUNNETT oscillator tuning





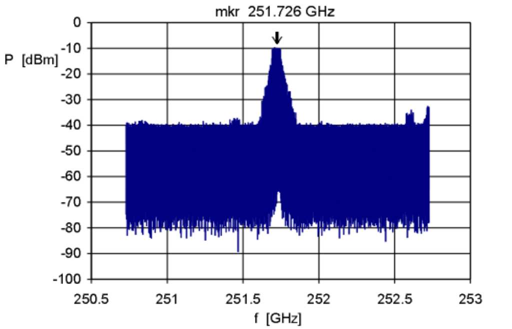


One TUNNETT structure in different resonator cavities - max. frequency limited by cavity Q not by GaAs structure



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

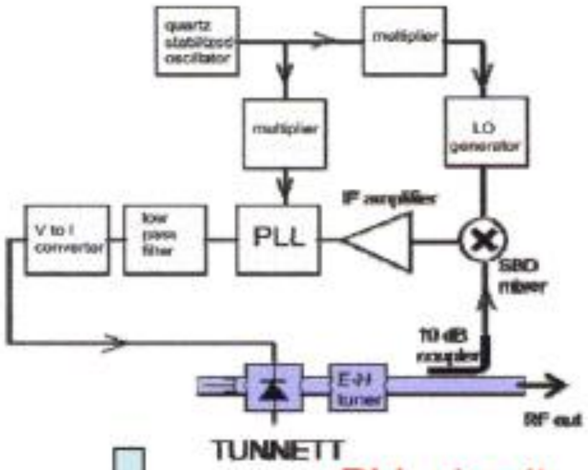


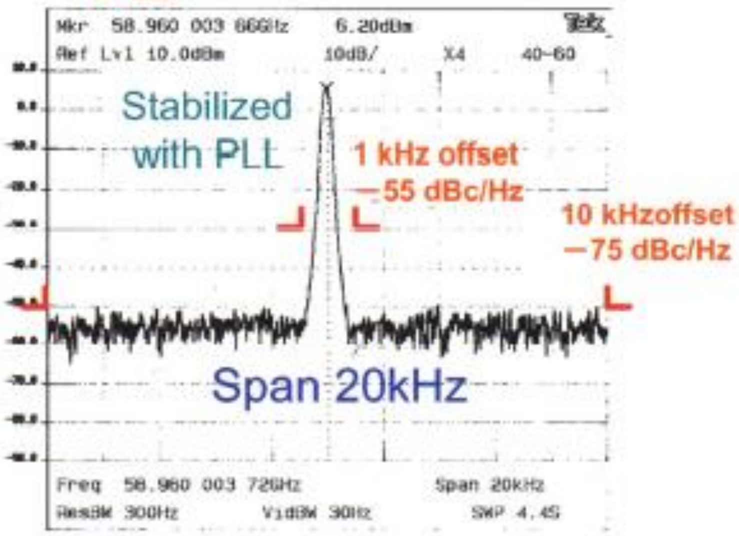
from 250.780 GHz to 252.780 GHz

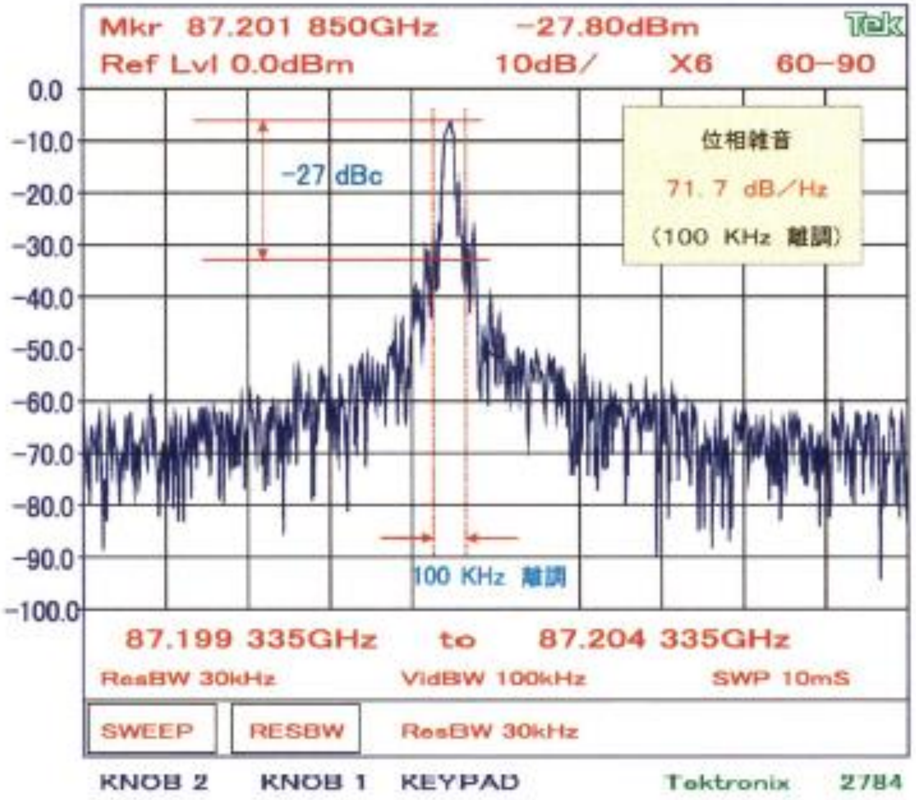
ResBW 1 MHz VidBW 7 MHz SWP 10 s Span 2.0 GHz

file: TUNET_2

TUNNETT Oscillator (with and without PLL)







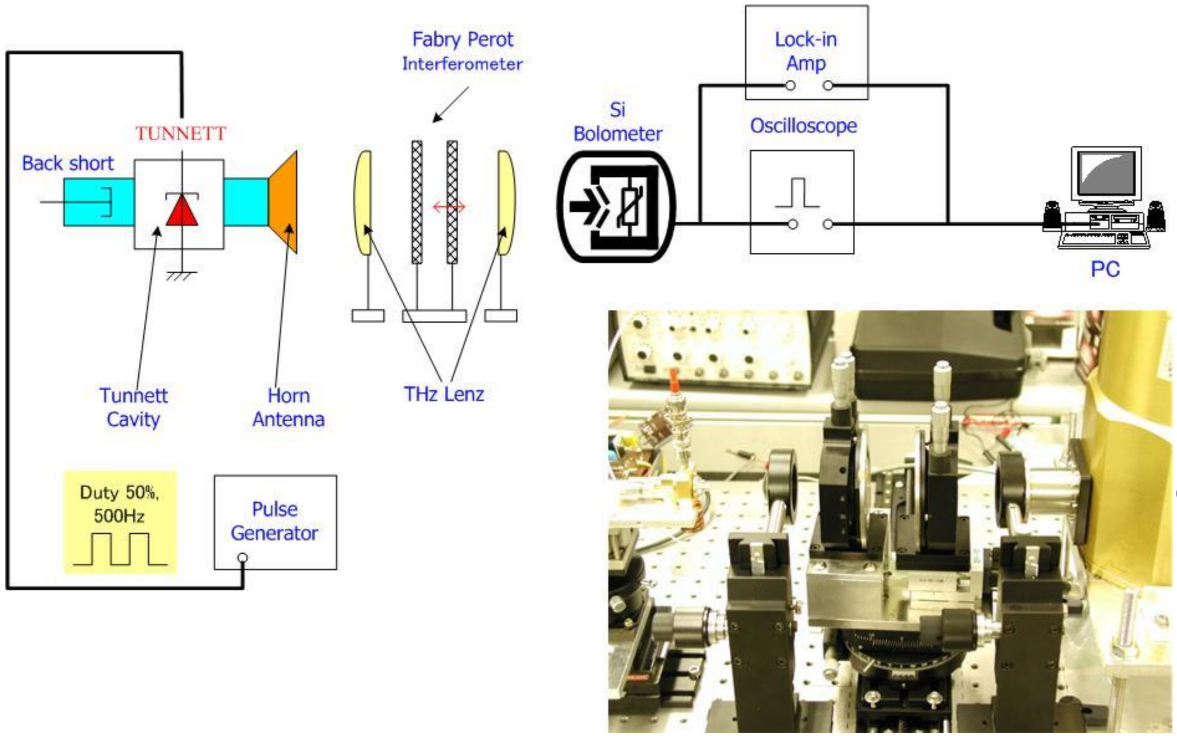
フリーランニングにおける低い位相雑音

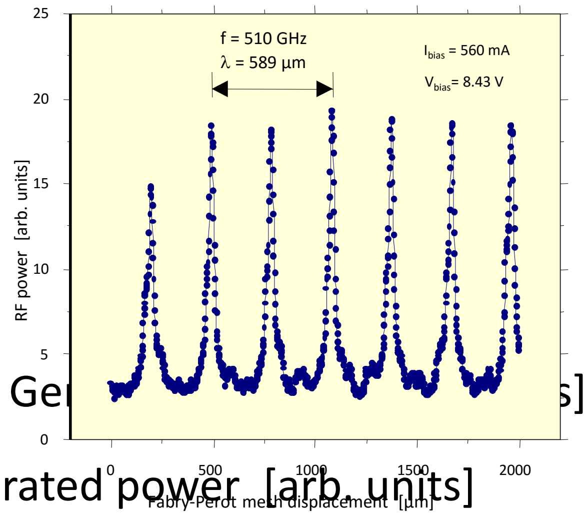
27 dB + 10log ResBW
= 27 + 10 log 30000
= 71.7 (dB)

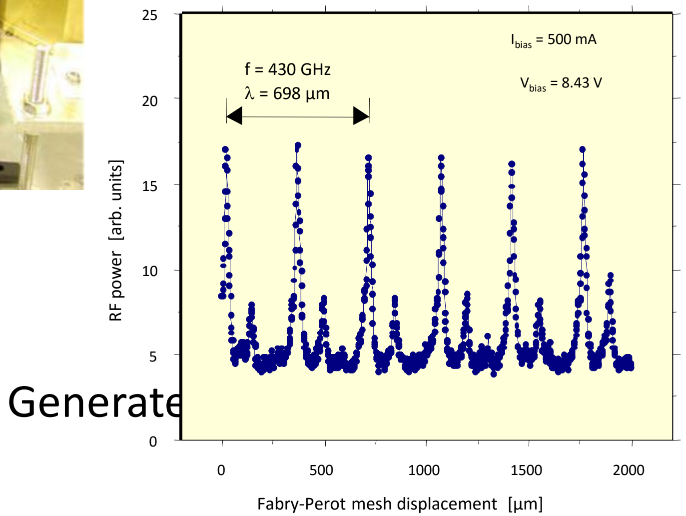
タンネットダイオードの発振スペクトル例(ファブリペロー測定系)

430 - 510 GHz CW, fundamental mode

WR-1.5 cavity (0.381 × 0.191 mm)



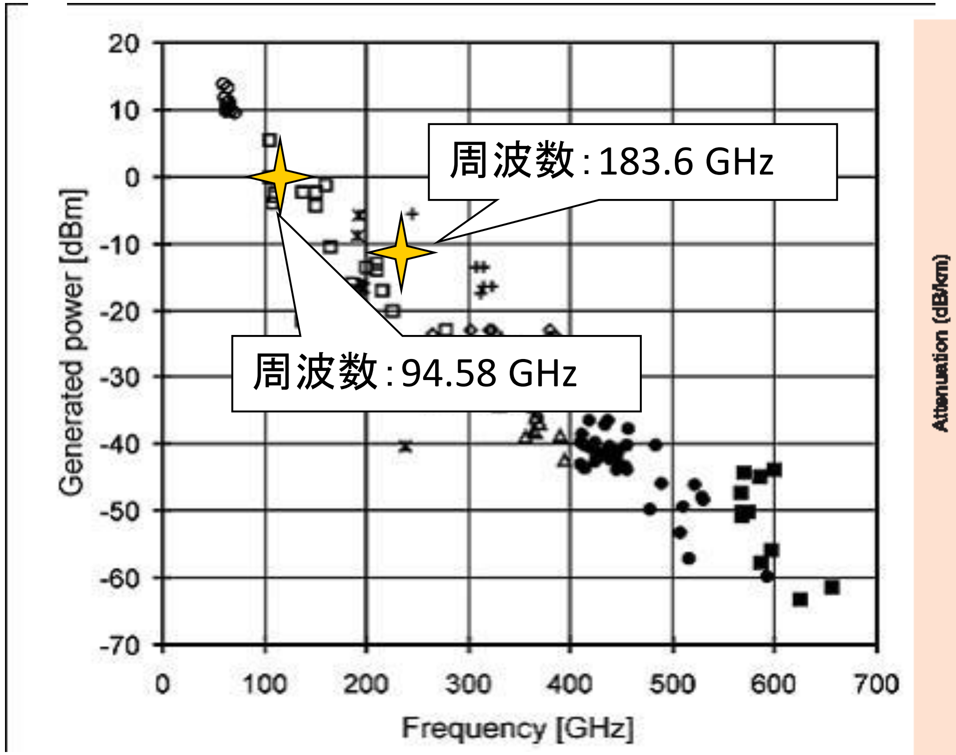




タンネット発振周波数測定システム
（ファブリペロー干渉計システム）

Application of sub-THz osc devices for imaging

タンネット発振器の周波数選択



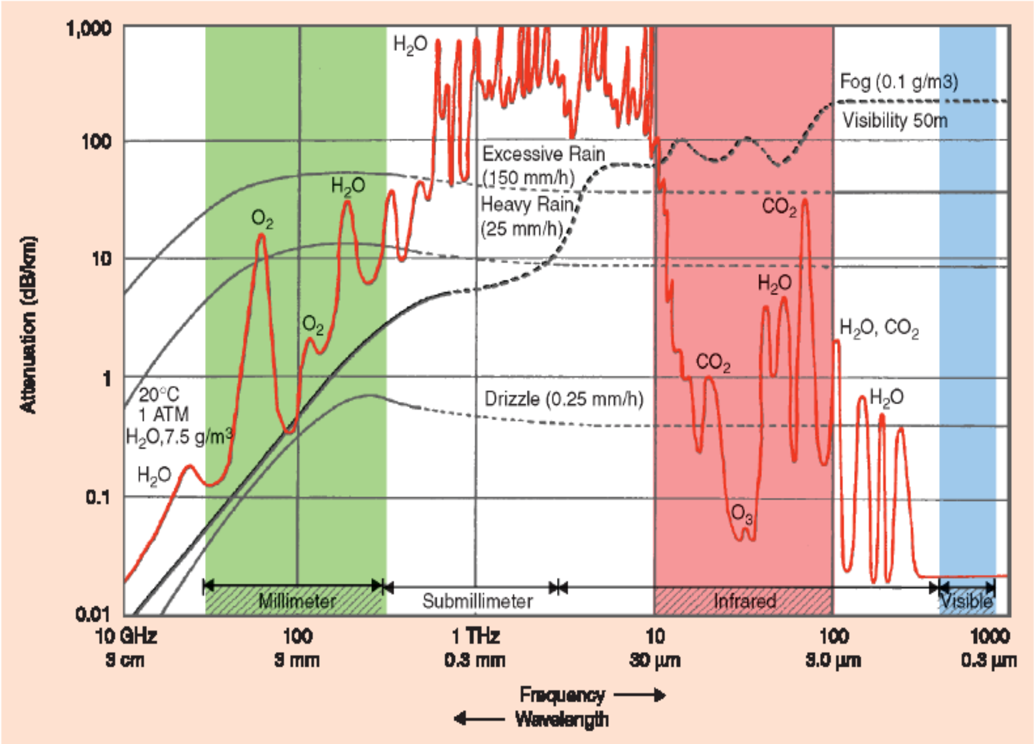


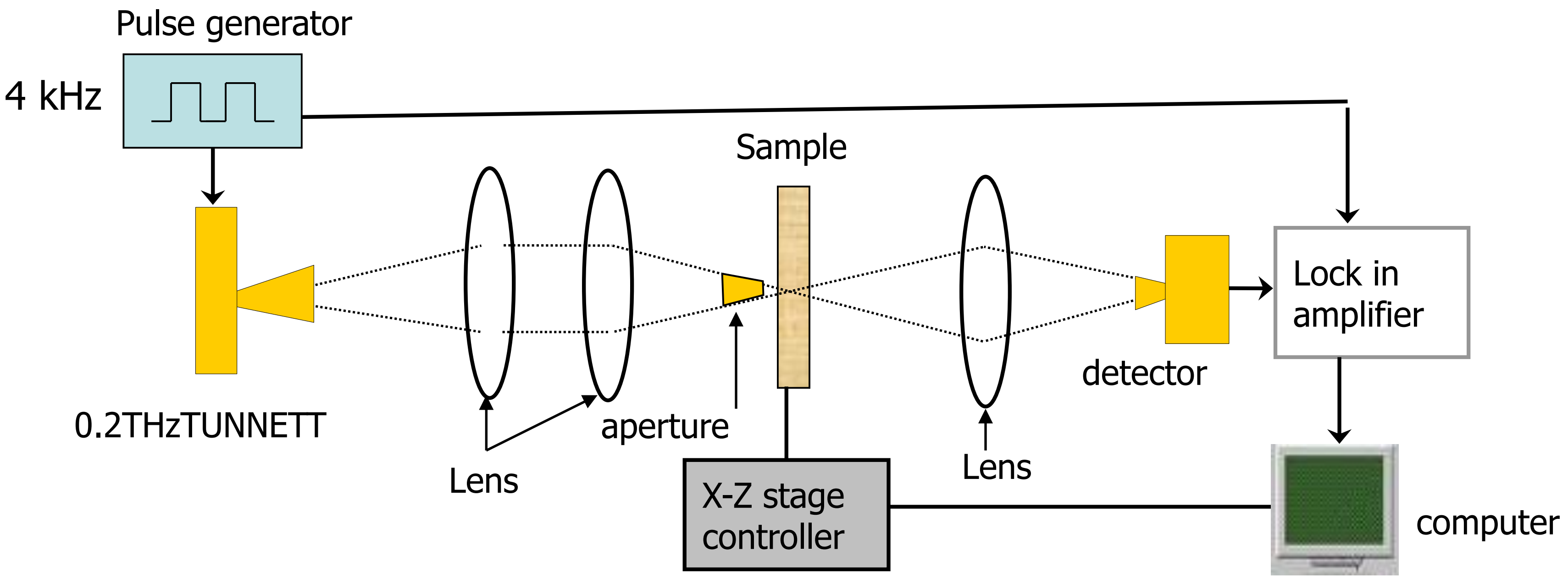
図1 タンネット発振出力の周波数依存性[1]　**図2** 大気および水による電磁波の減衰[2]

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

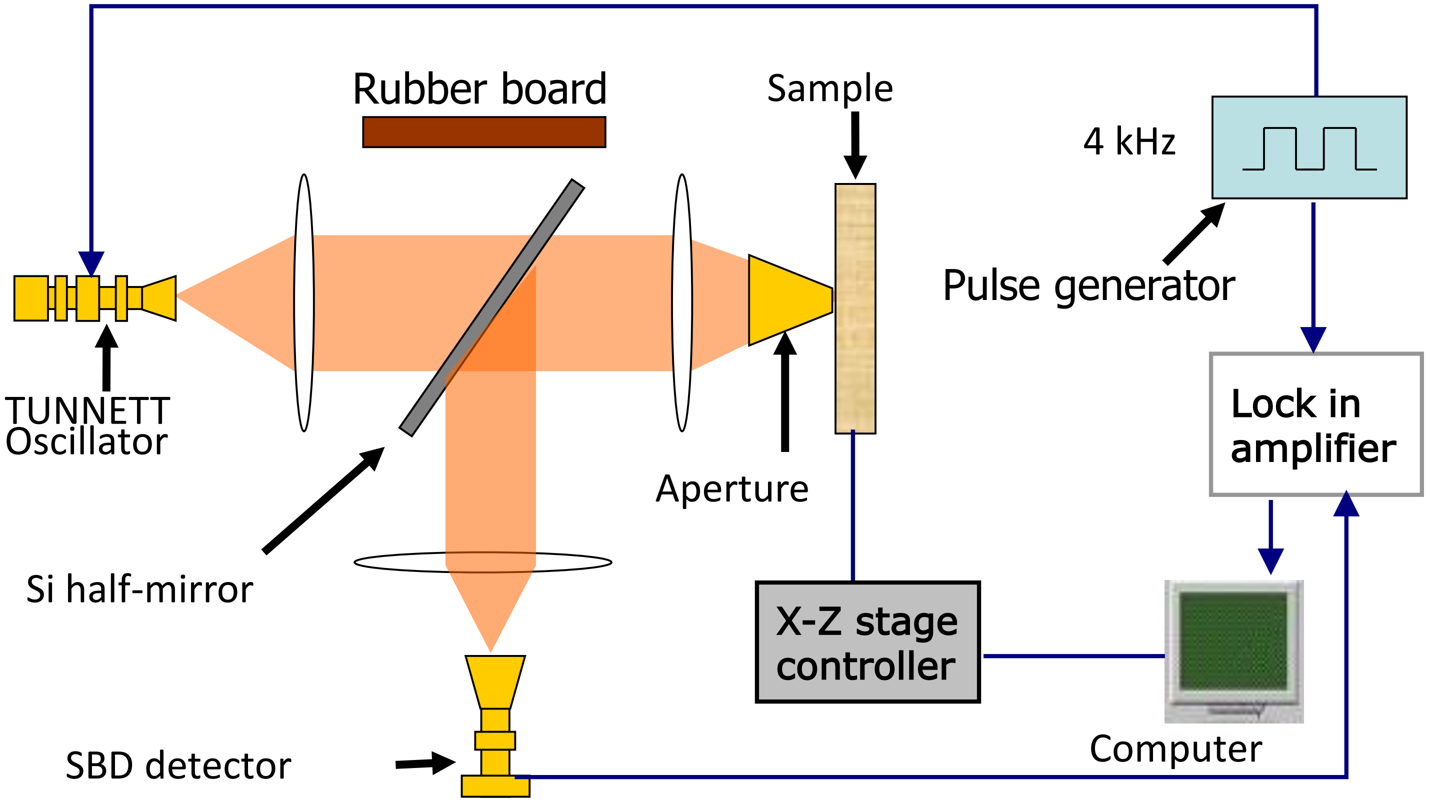
サブテラヘルツイメージング測定装置

- 透過イメージング装置

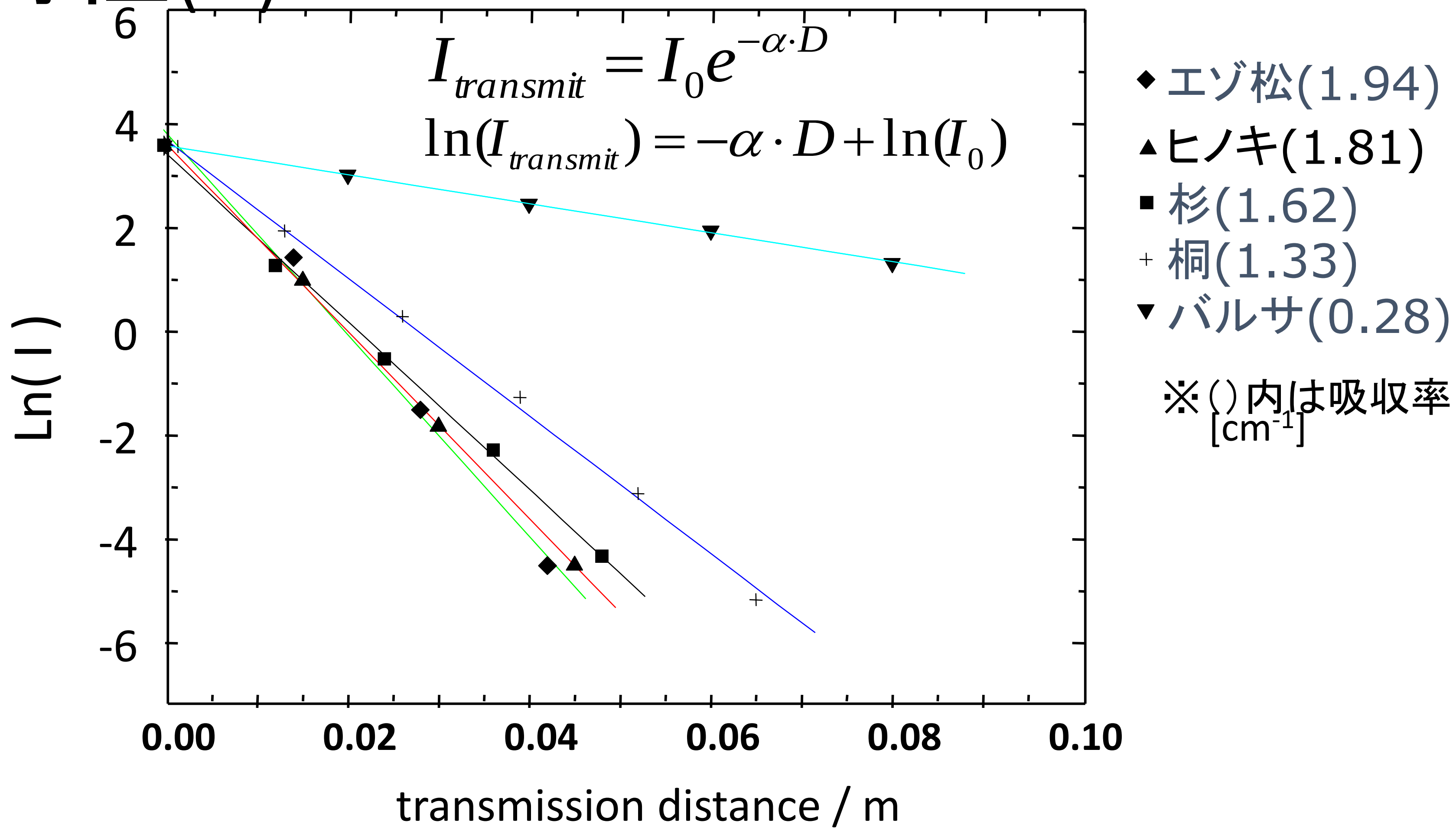


サブテラヘルツイメージング測定装置

- 反射イメージング装置

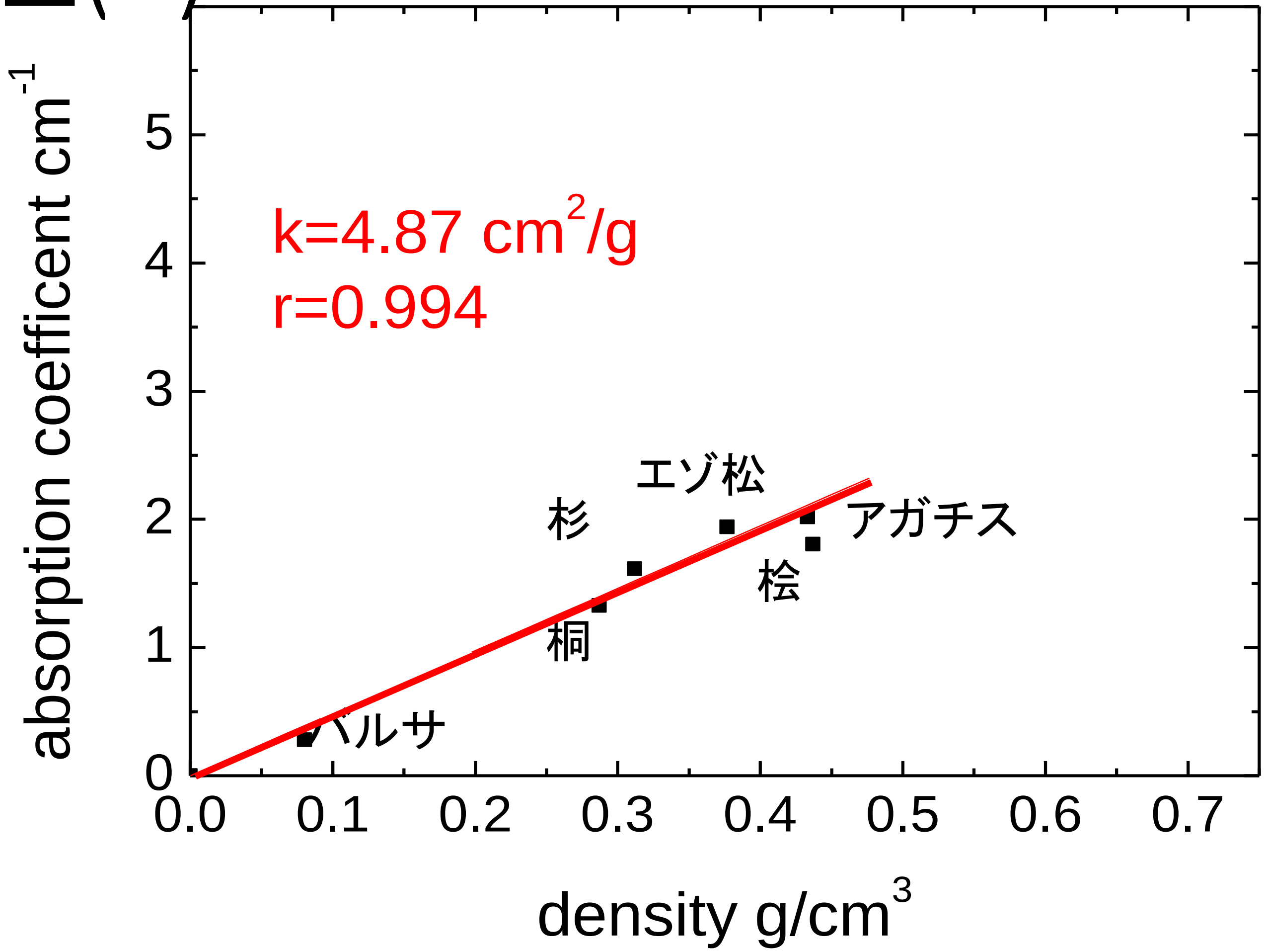


透過特性(1)



強度と透過距離は指数関係

透過特性(2)

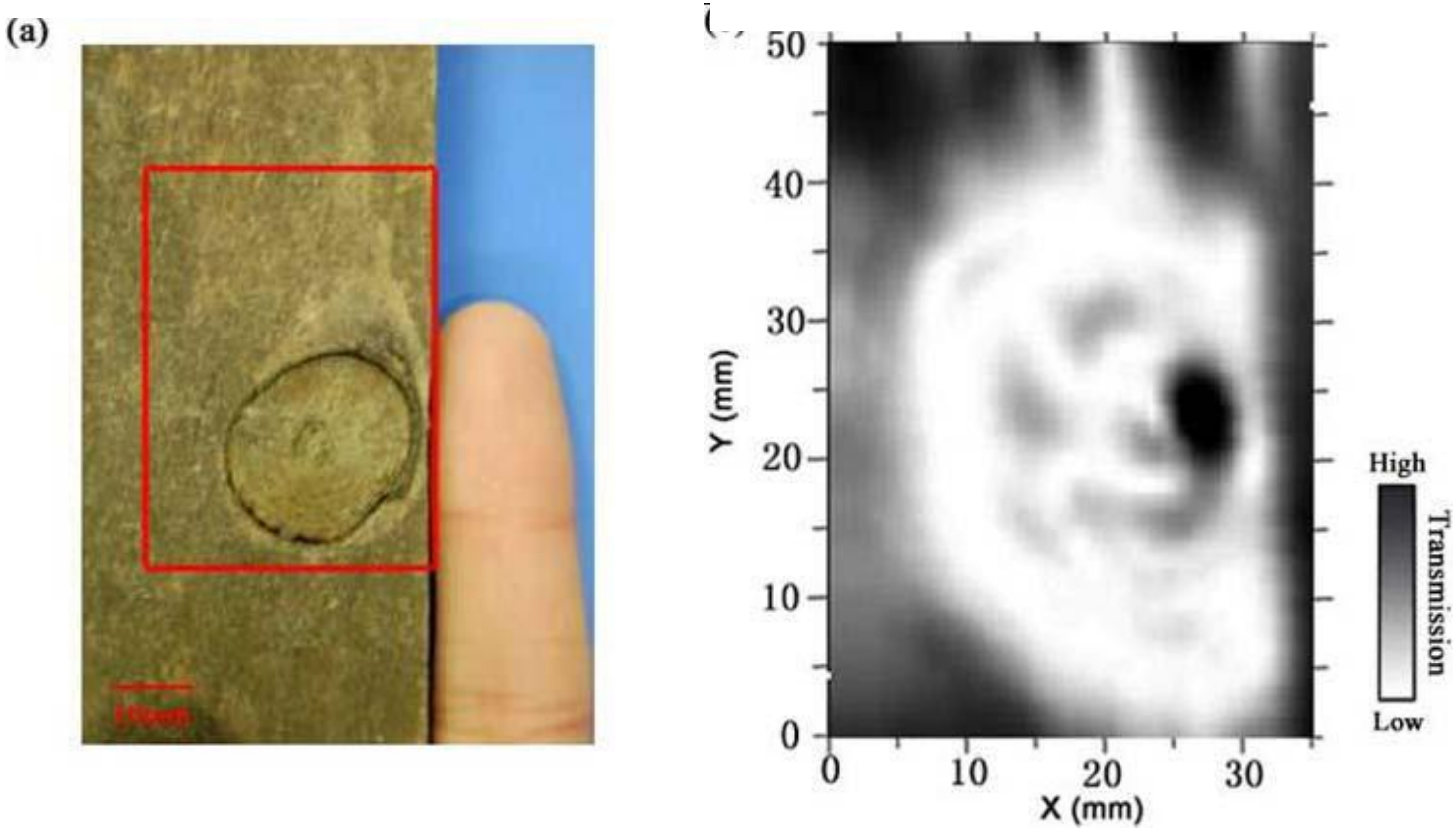


→ 吸収係数と密度は比例関係

不均質構造の透過測定

- 節のイメージング

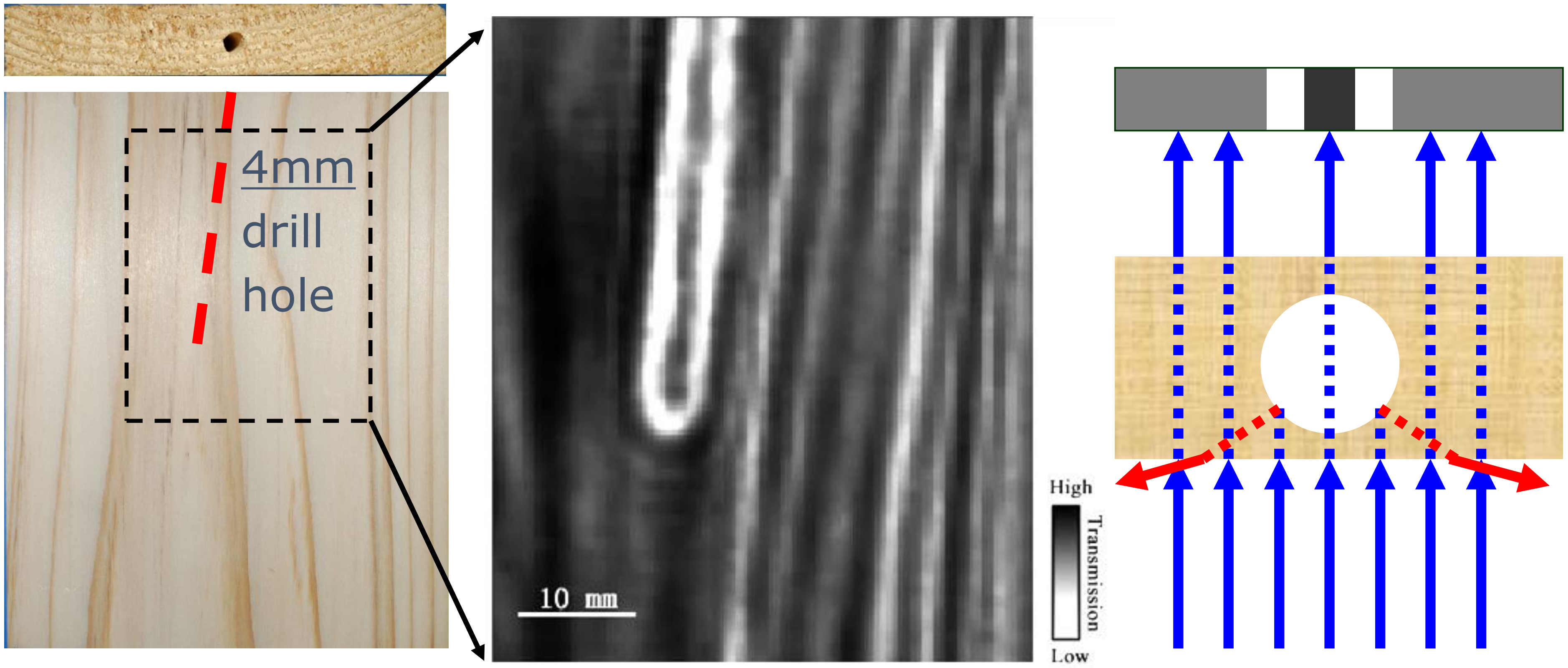
試料: 杉
厚さ: 20 mm



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ー透過測定

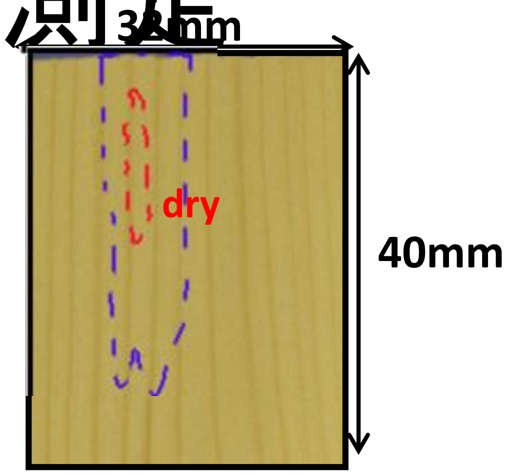
- 欠陥：過剰水分（浸潤測定）

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

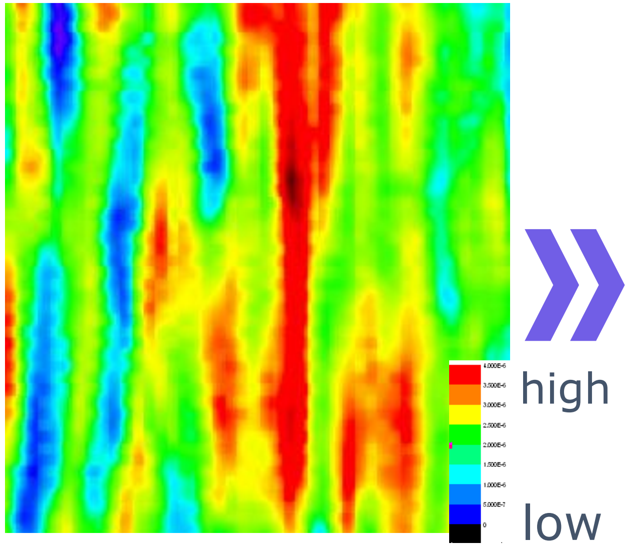
↓

水も透過してしまうX線では困難

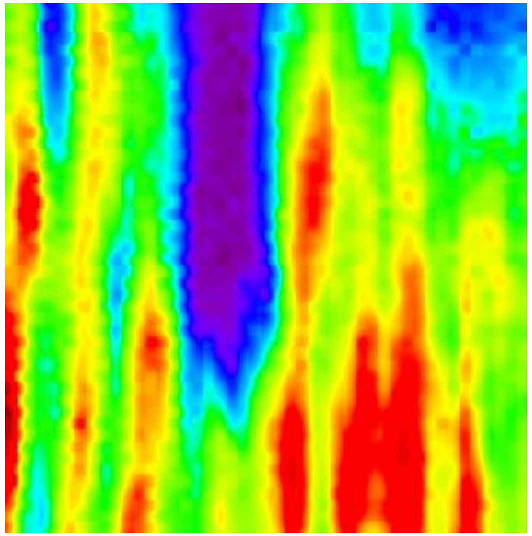
試料：トウヒ
厚さ：14.2 mm



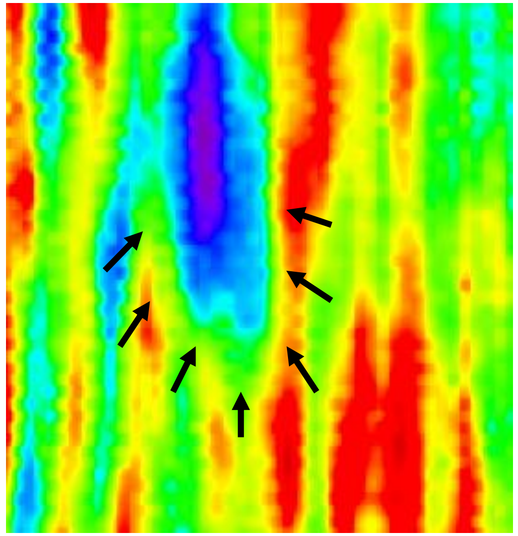
水注入前



水注入直後



乾燥後



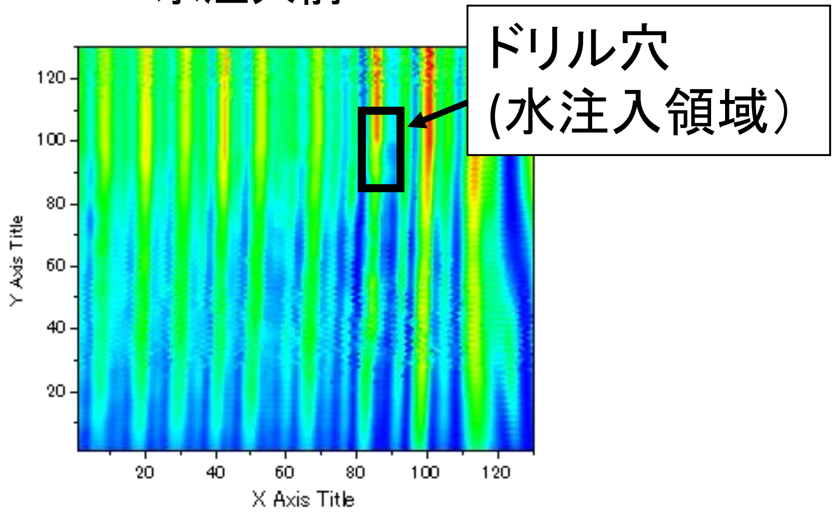
木材内部への水の浸潤—反射測定

試料：杉
厚さ：12 mm

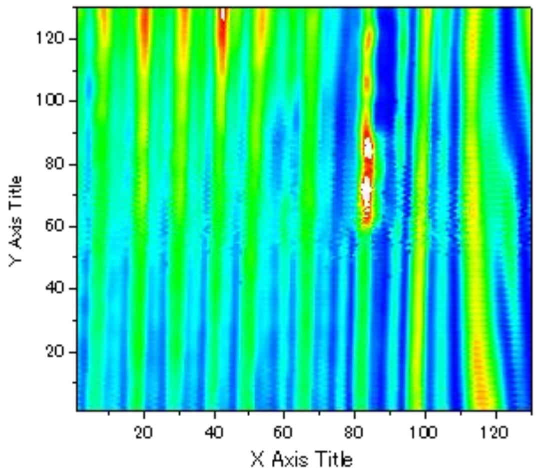
ドリル穴(5 mm径)に水を注入

反射測定

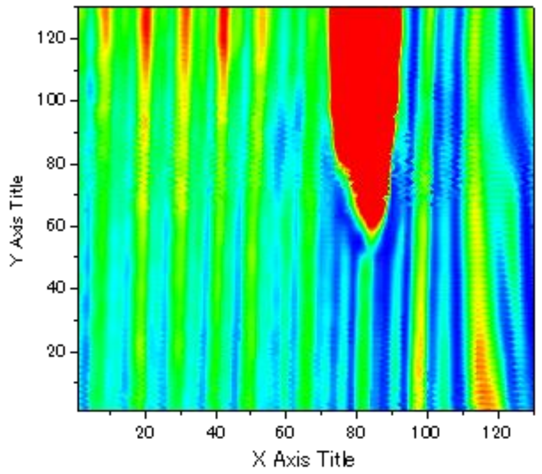
水注入前

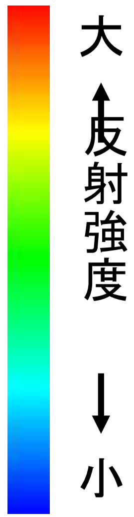


水200 ml

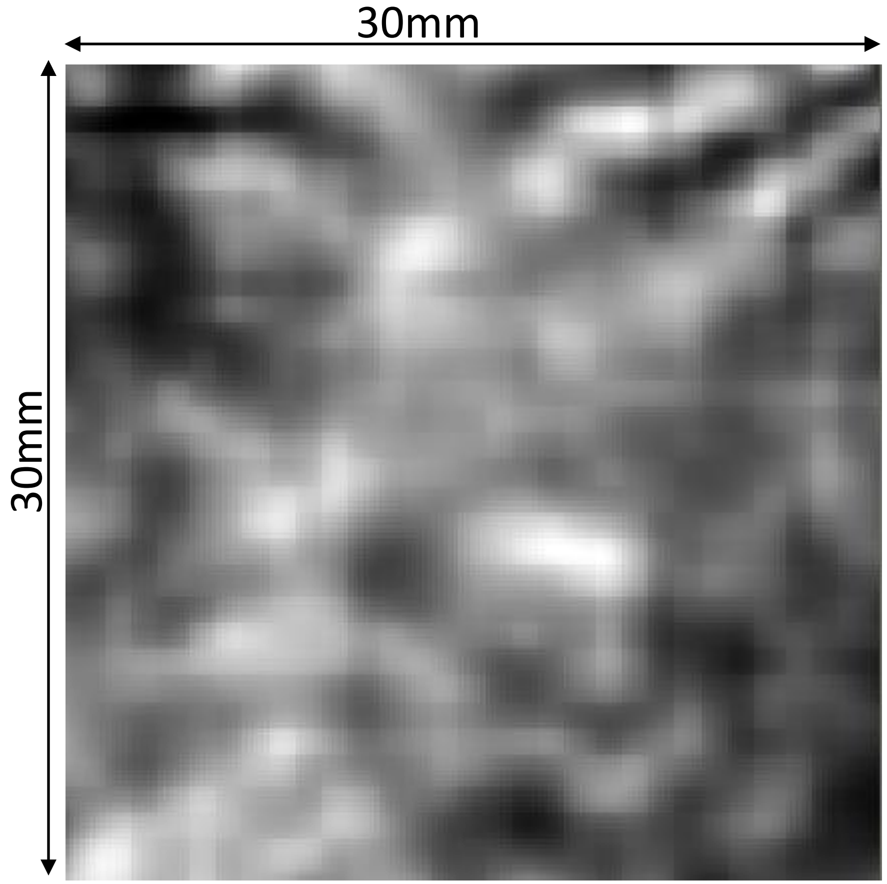


水400 ml

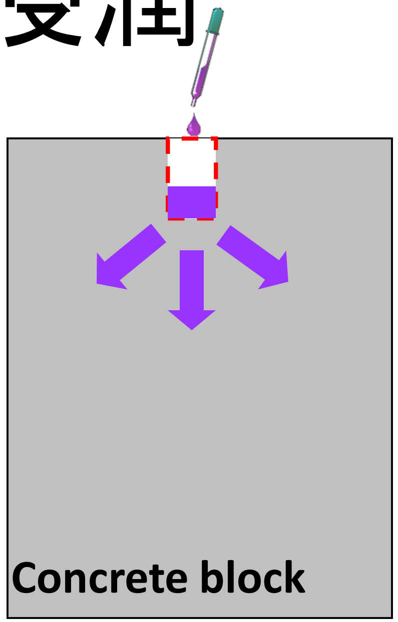




コンクリート内部への水の浸潤

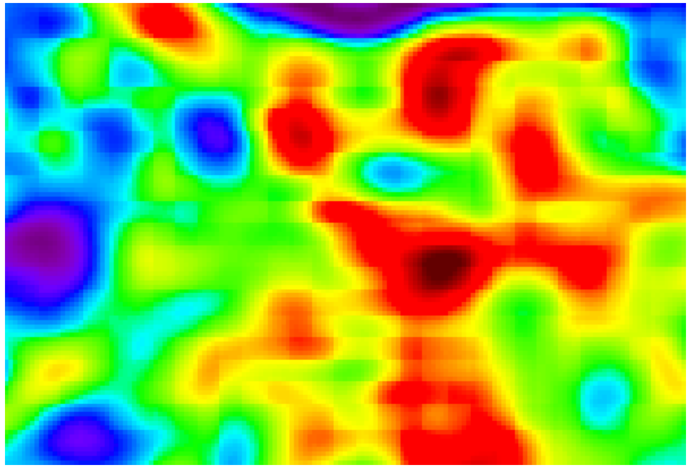


コンクリート(厚さ10mm)内部における
水の浸潤の様子(透過測定)

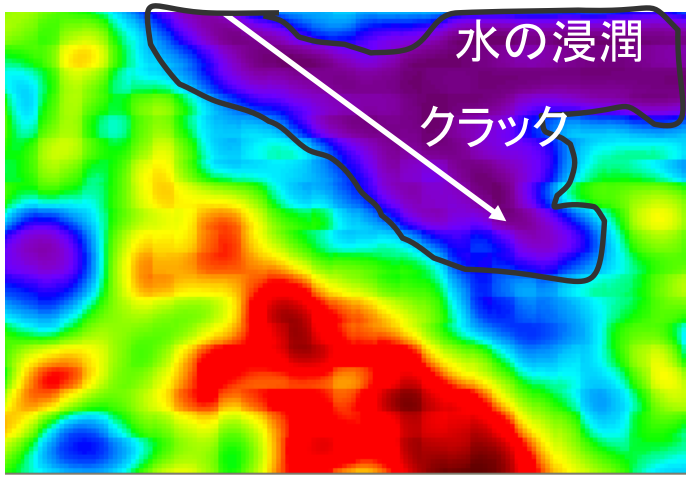


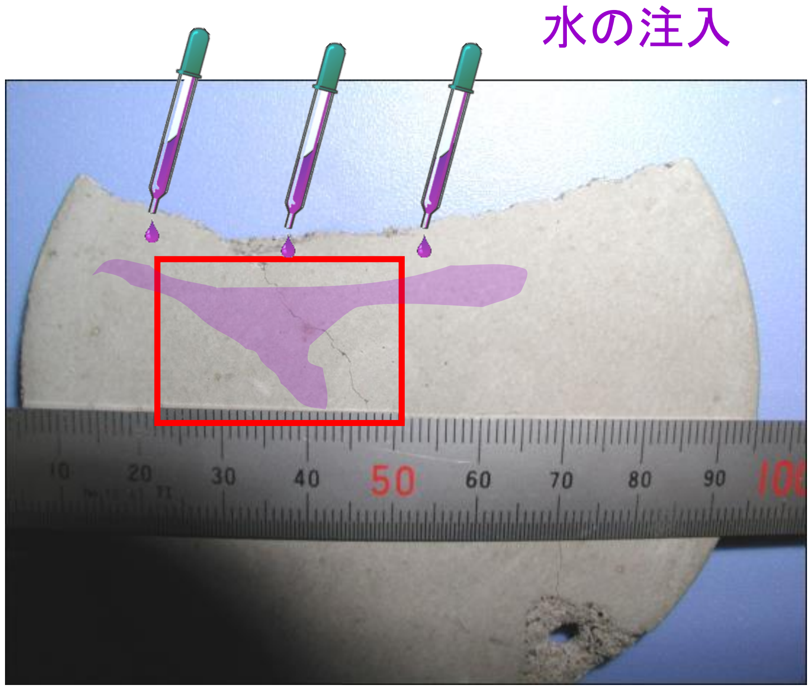
クラックの透過測定

水注入前



水注入後



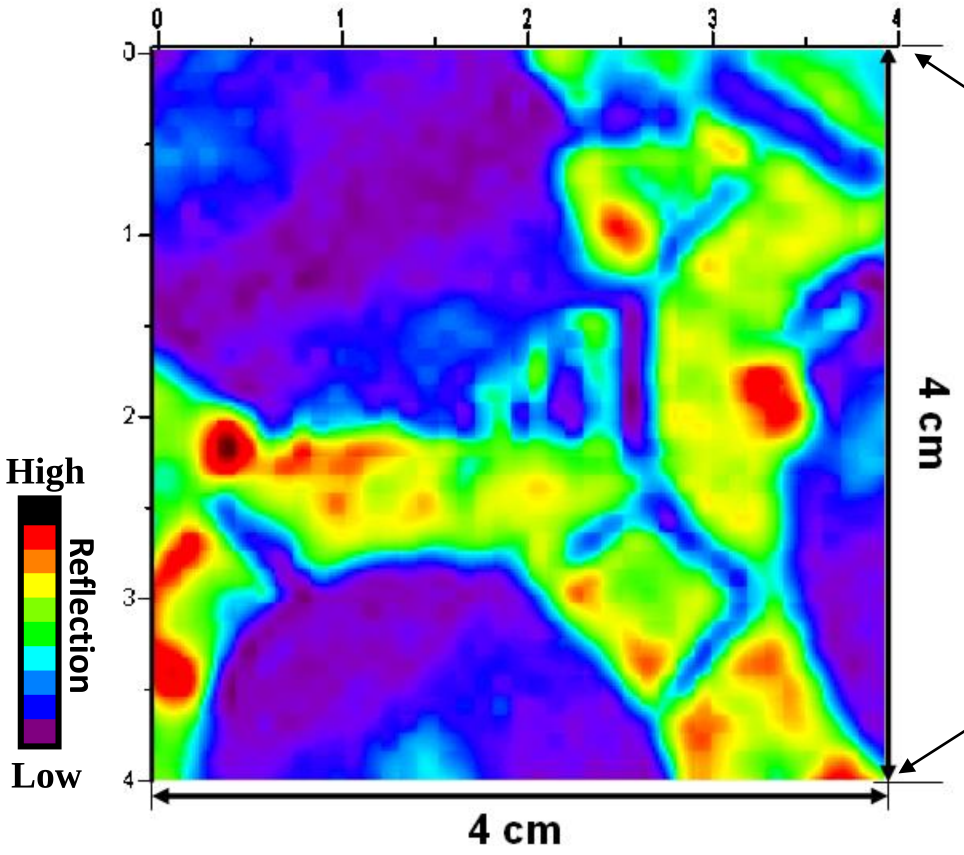


クラック周辺の水によるテラヘルツ波の吸収

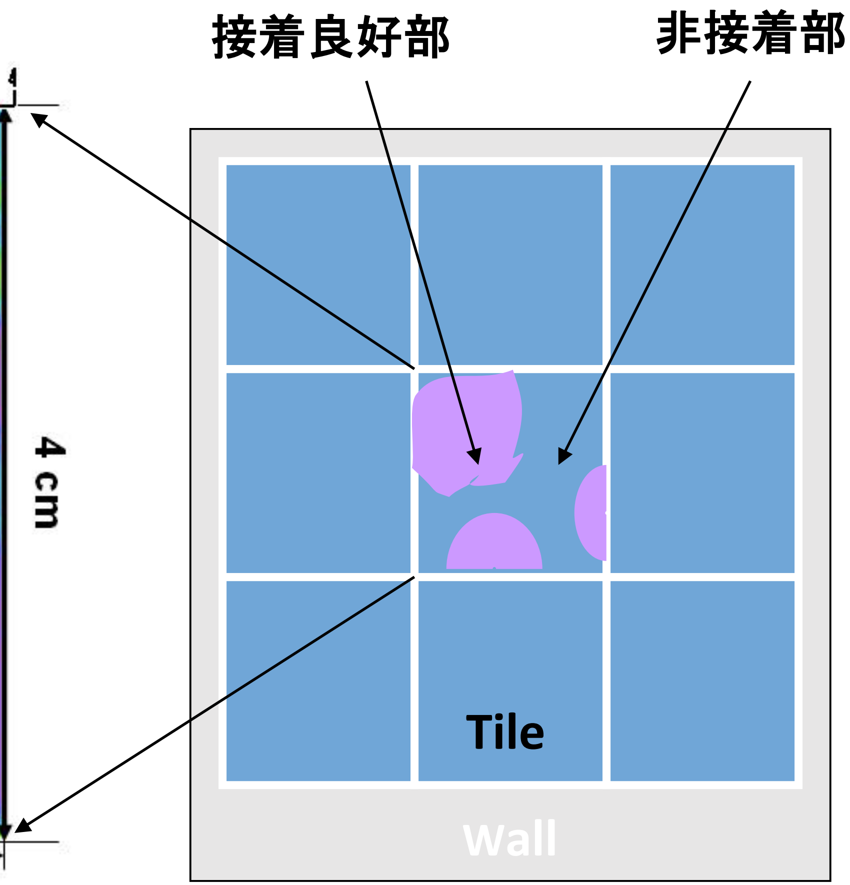
↓

クラック検出の手がかり

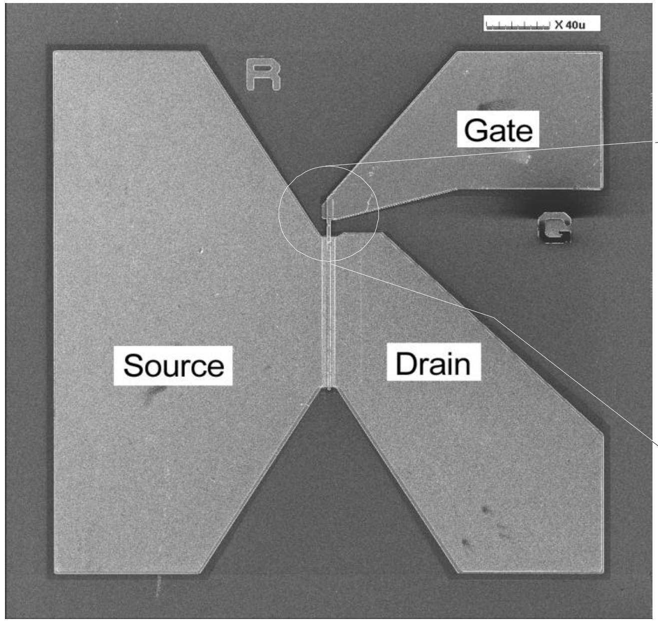
セラミックタイルの接着不良欠陥



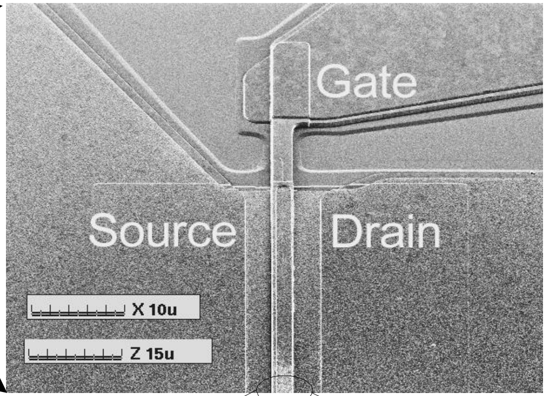
反射測定におけるセラミックタイルのイメージング画像

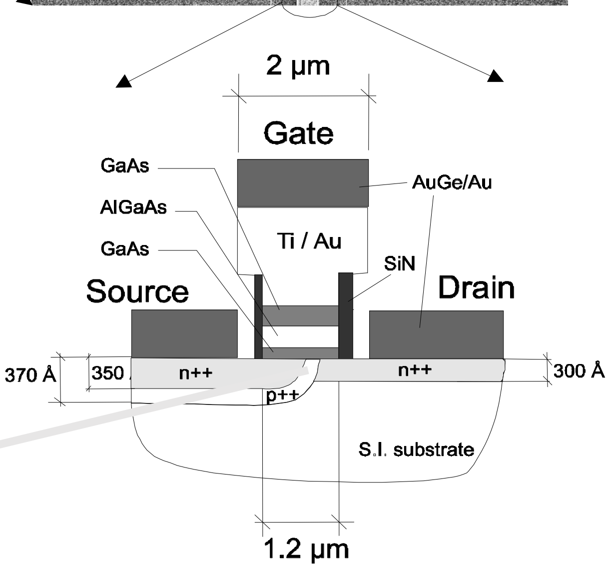


Pattern layout of ISIT for DC evaluation



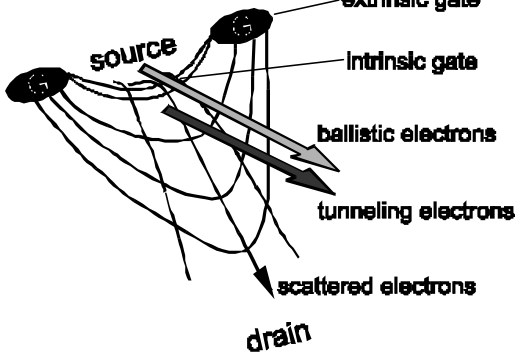
Implemented with molecular layer epitaxy



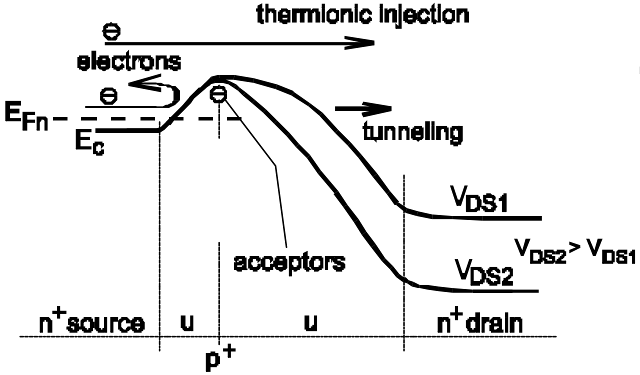


ソース･ドレイン間距離
3.5nm（13原子層）

operation principle of ISIT



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



Ballistic electron transport

Theoretical operation frequency: up to 800GHz

Improved performance by tunnel conduction

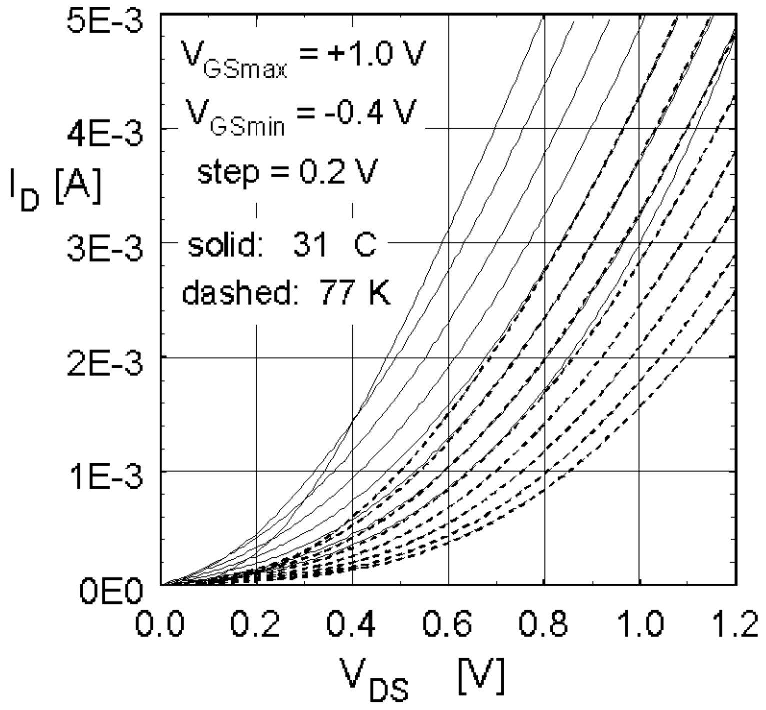
✧ISIT(Ideal Static Induction Transistor) invented in 1979 by J.Nishizawa (J. Nishizawa, Proc. 1979 IEEE Int. Conf. Solid State Devices, 1979.)Washington DC

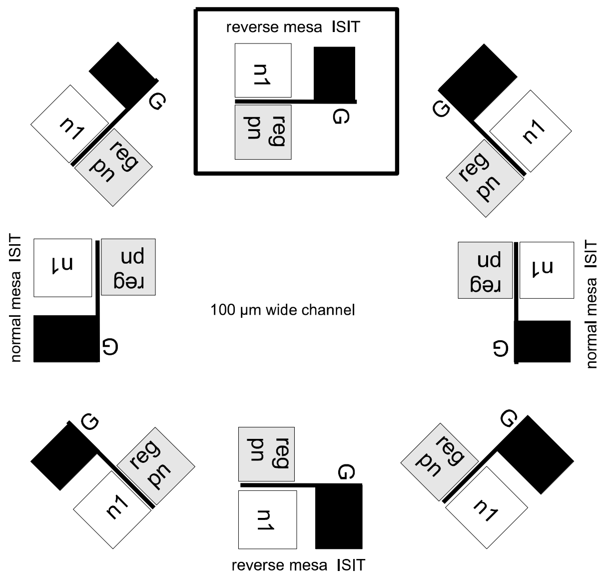
•*ISIT DEVICE PERFORMANCE (S/D 10nm Tr.)*

E/D(enhancement/depletion) mode operation by MIS gate

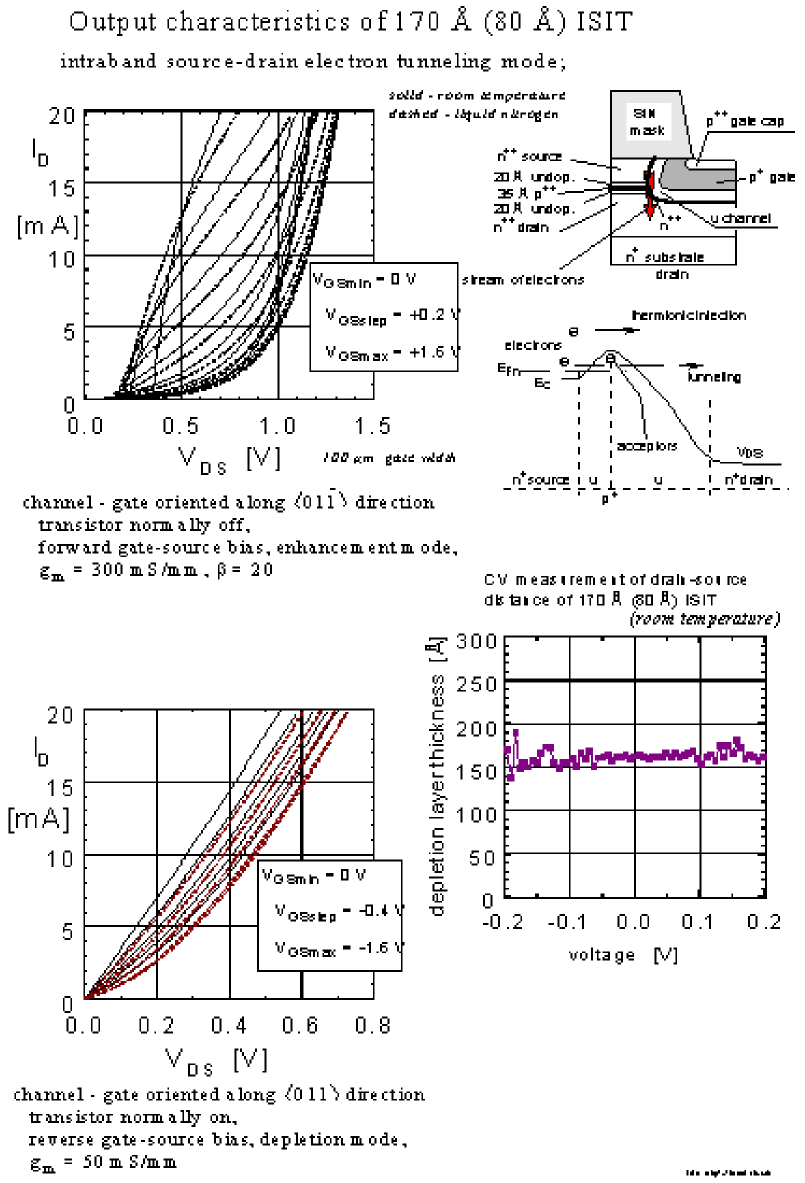
DC output characteristics of S/D ***10nm*** ISIT with regrown-AlGaAs MIS gate operated with E/D mode g_m>300mS/mm

β>20





True S/D 10nm ?



Y.Oyama, P.Plotka and J.Nishizawa, Applied Surface Science, 82/83 (1994) 41-45.
P.Plotka, T.Kurabayashi, Y.Oyama and J.Nishizawa, Applied Surface Science, 82/83 (1994) 91-96

Quiz

Band gap of active region of LD is 1.0eV. Give the emission wave length in micron unit.
1 micron [mm] = 1x10^{-6}[m].
Where electron charge q is 1.602x10^{-19} [C], Plank constant h is 6.626×10^{-34}[J・s], light velocity in vacuum c is 3×10^{8}[m/s].

半導体レーザの活性層が、禁制帯幅Egが1eVである材料で形成されている。レーザ発振される光の波長をミクロン単位で答えなさい。
但し、1eVは1個の電子が1ボルトの電位差で加速された時に、電子に与えられるエネルギーに相当し、電子の電荷量qは1.602×10^{-19}[C]とする。またプランク定数hは6.626×10^{-34}[J・s]で、真空中の光速cは3×10^{8}[m/s]である。
ここで、光量子仮説によれば、

$$E = h\nu$$

$$\lambda = \frac{c}{\nu}$$

で、ν は光の振動数である。