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

- **<u>Material issue of semiconductor devices and fabrication process</u>**
- Schematics of thin film growth (Molecular Layer Epitaxy, etc.)
- Ultra fast and high frequency semiconductor electronic and photonic devices -1
- Ultra fast and high frequency semiconductor electronic and photonic devices -2
- Crystal growth and semiconductor device epitaxy
- Device grade evaluation of semiconductor crystals

Optical fiber network in Japan&Worldwide

Background: activities in Tohoku University

Semiconductor laser (1957)

Light source

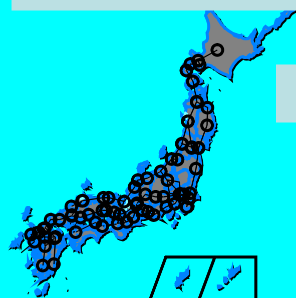
Optical fiber
Graded Index fiber (1964)

propagation

Avalanche photodiode
pin photodiode (1950)

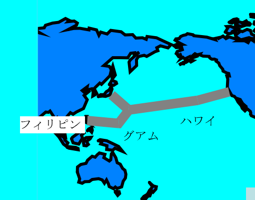
detection

Optical fiber network (NTT)



Fiber network (domestic)

Oversea cable



Pacific ocean

Total length 13200km

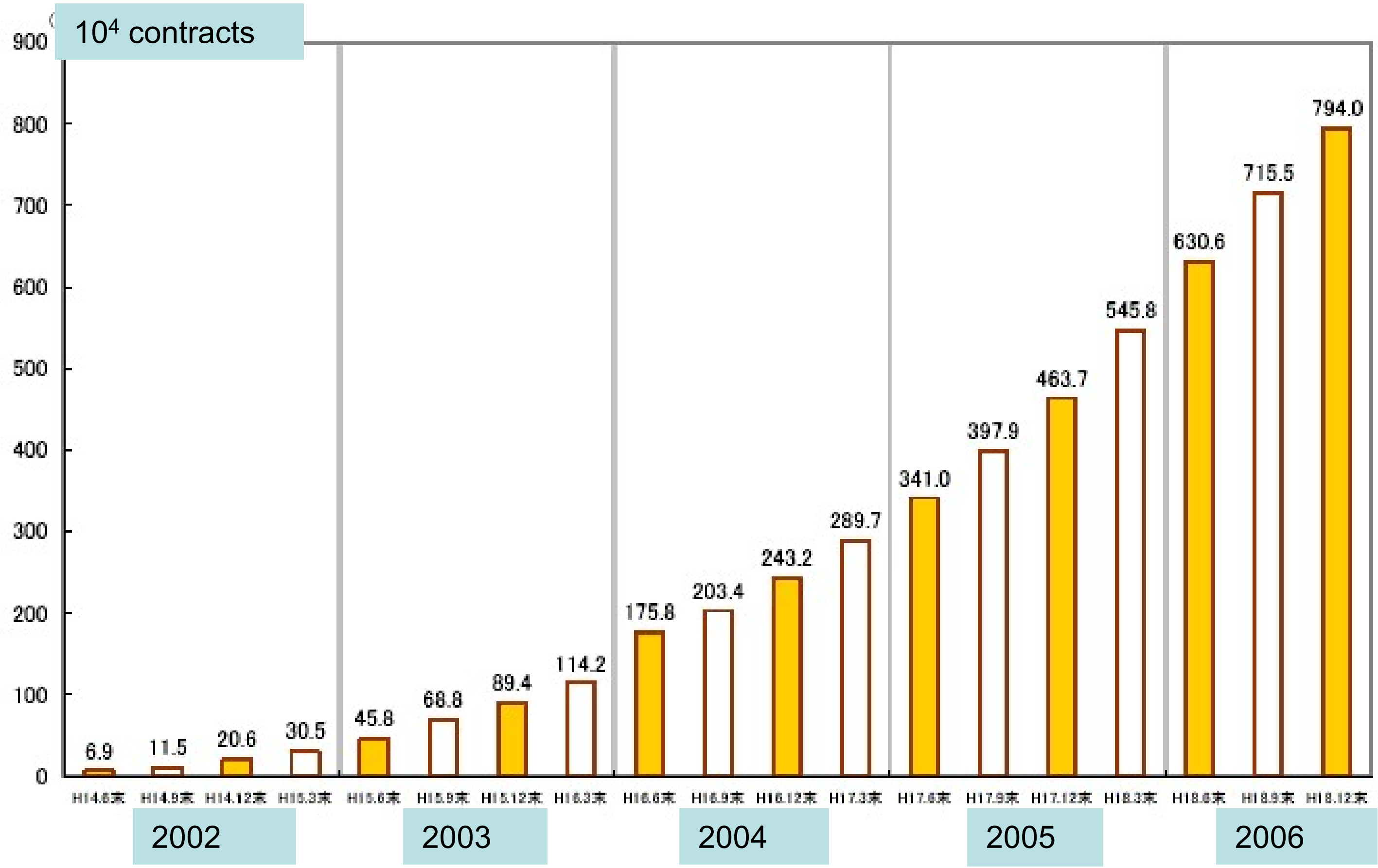
Fiber cable under the sea
(Kagoshima-Okinawa 1000km)

Fiber To The Home(FTTH)

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

No. of contract of FTTH service in Japan

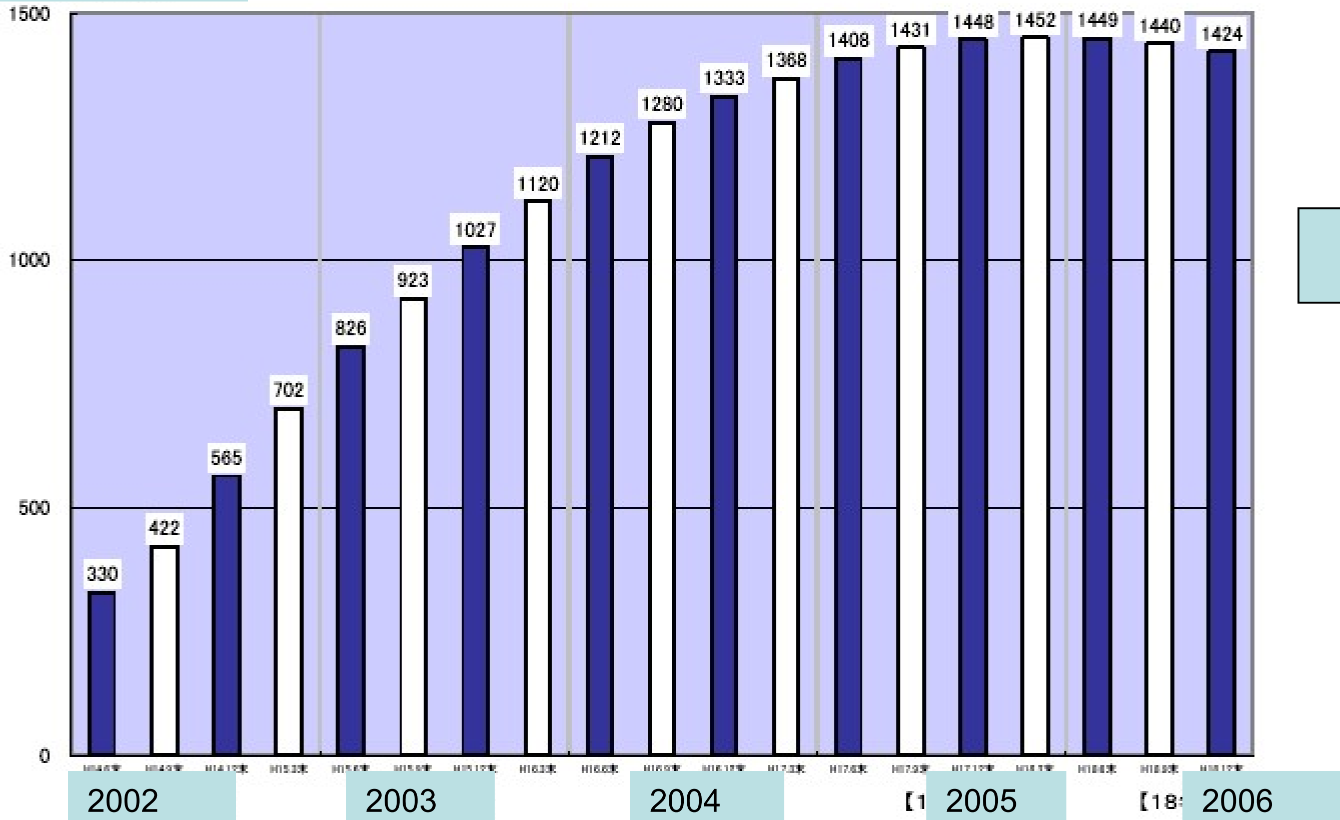


FTTH Fiber To The Home

NO. of contract of DSL service

saturation

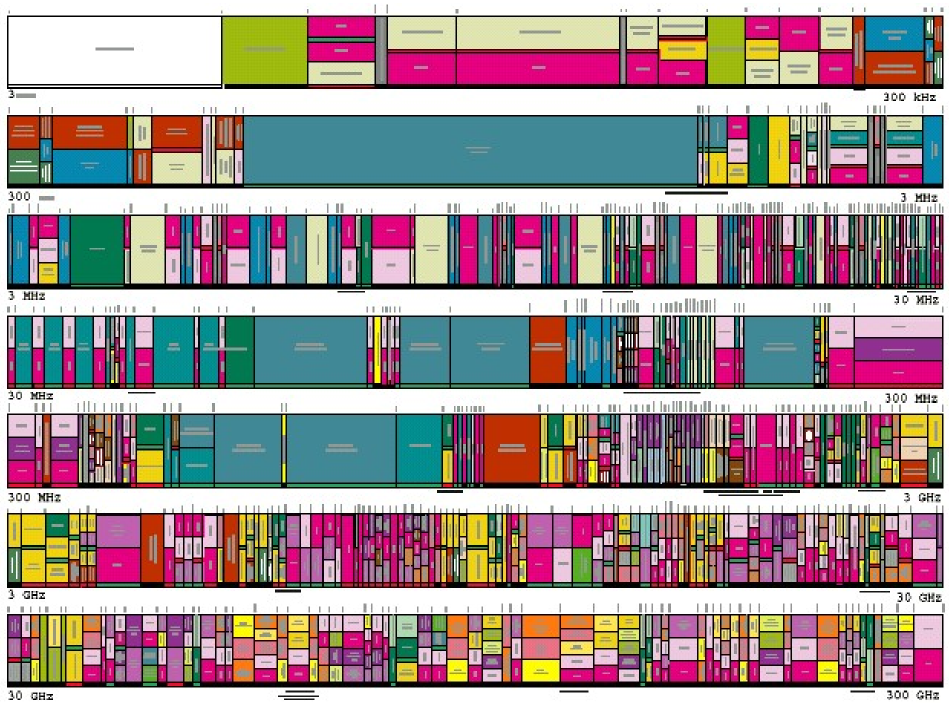
10^4 contracts



decreased

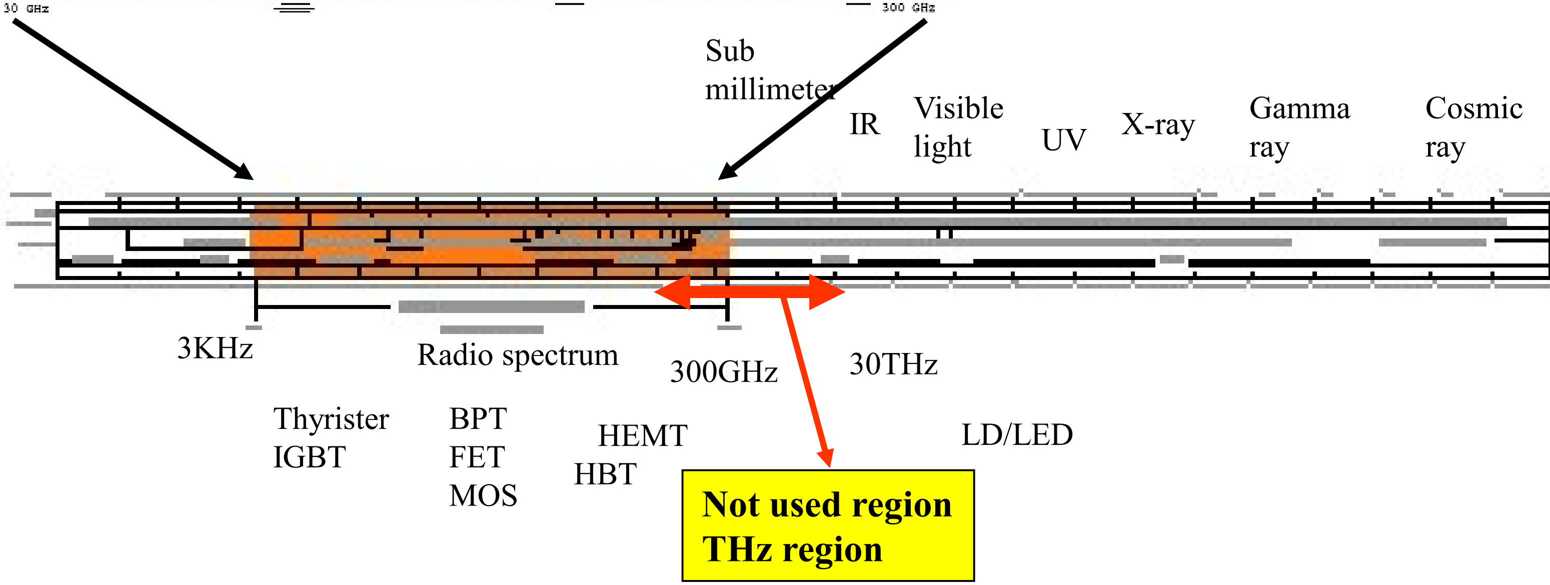
DSL 【xDSL】Digital Subscriber Line

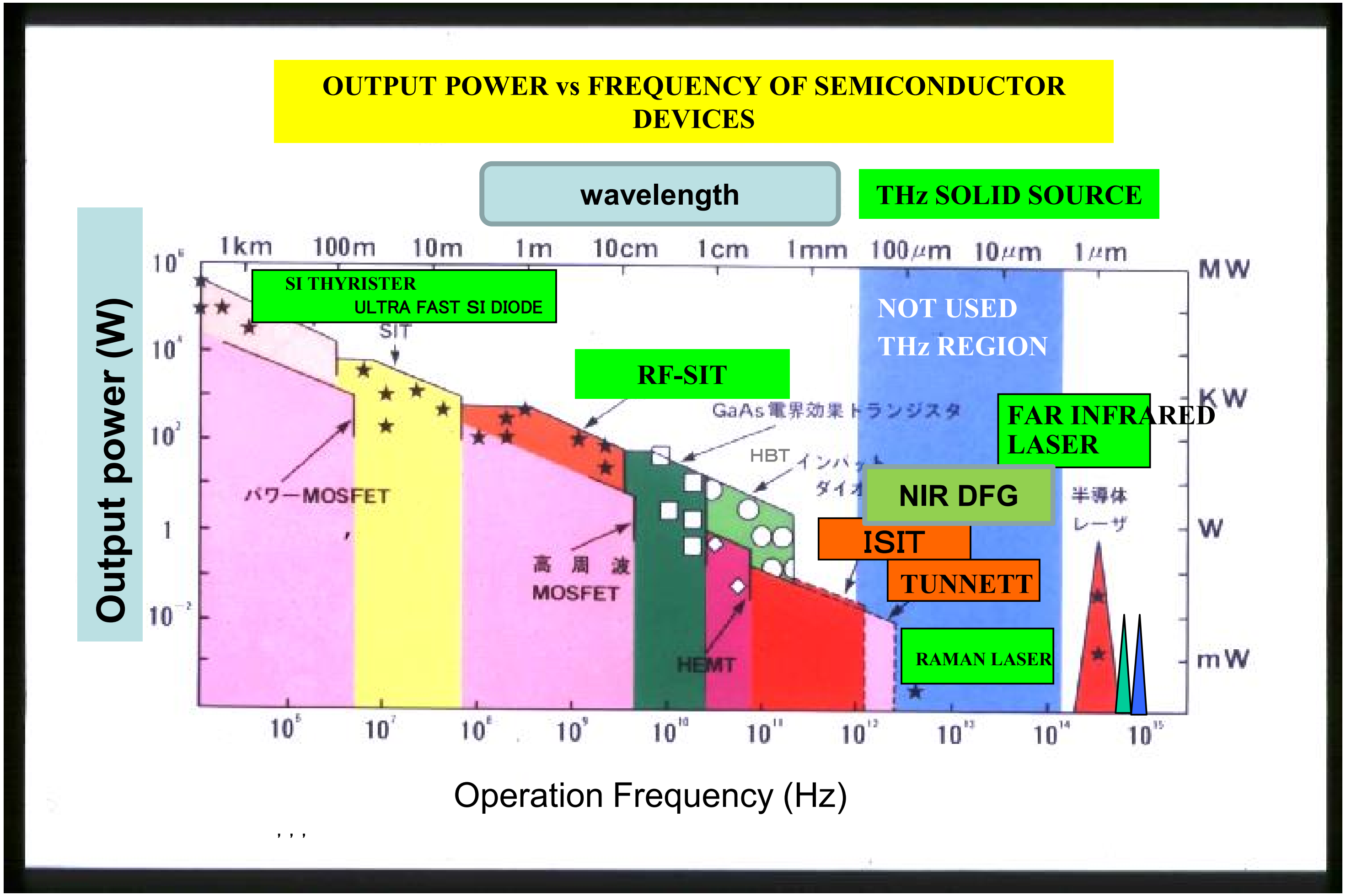
Frequency Allocation (USA)



Our target device for not-used THz region

ISIT
TUNNETT
(Semiconductor Raman laser) -30THz





*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

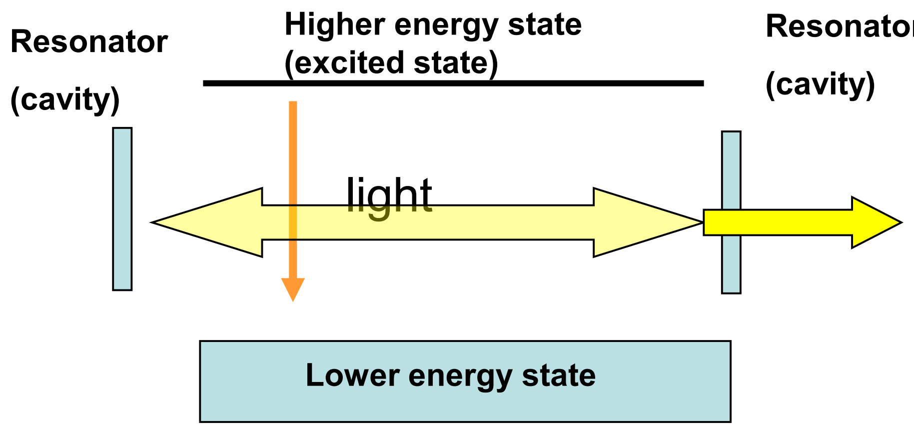
Light **A**mplification by **S**timulated **E**mission of **R**adiation

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 emission（誘導放出）

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

Characteristic feature of laser

Phase term

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

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

<u>Glass fiber</u>

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

Light source → Propagation line → Light detector

<u>Semiconductor laser</u>
(semiconductor maser: Tohoku univ.)
Light emitting diode

***<u>pin</u>* <u>photo diode</u>** (fast response)
Avalanche photo diode (high sensitive amplification)
Tohoku Univ.

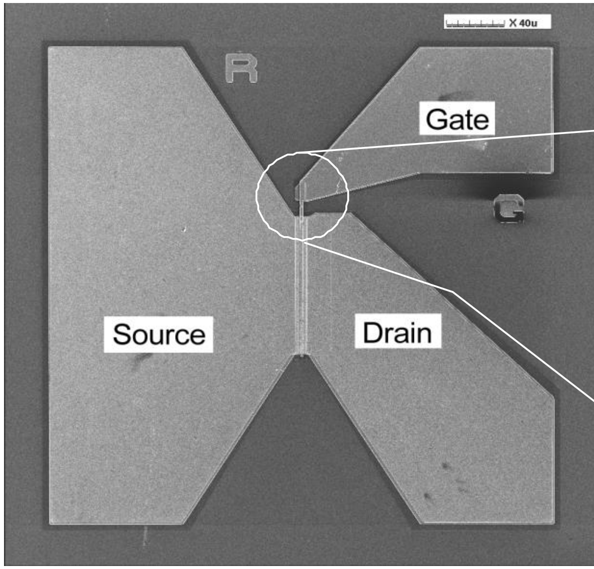
modulation

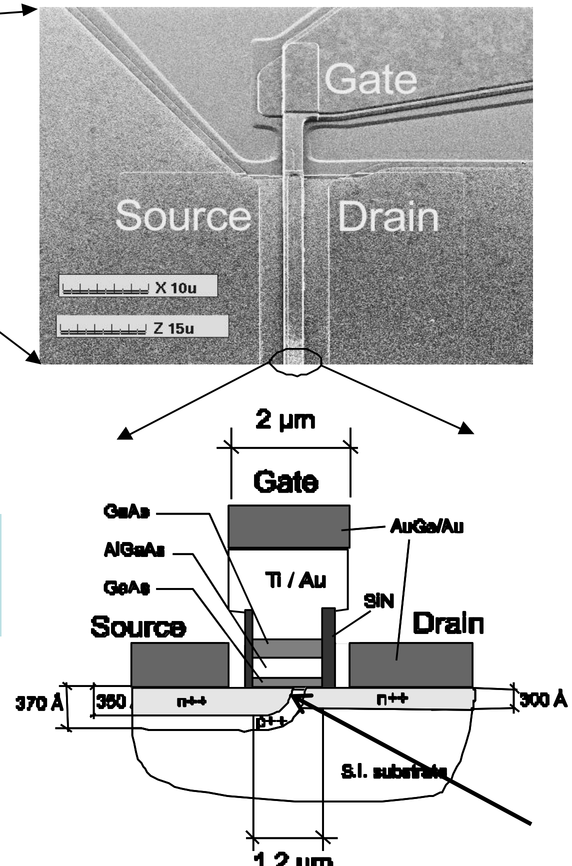
Static Induction Transistor (Tohoku Univ.)

demodulation

Static Induction Transistor
Semiconductor Raman Laser

S/D 4nm Transistor for THz freq.





Source/Drain 4nm

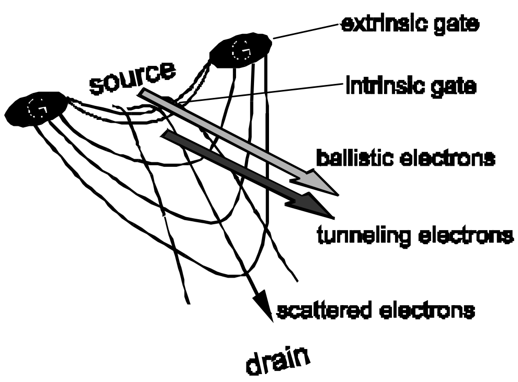
Transit time due to ballistic electron transport

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

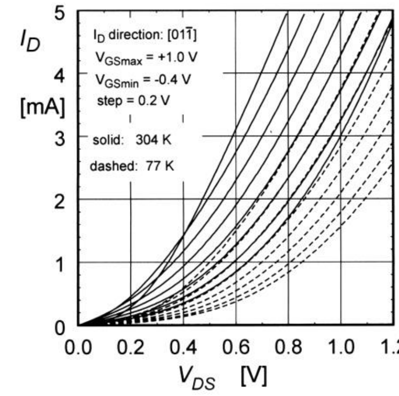
$$\leq 0.16\,ps$$

4nm channel length transistor structure

operation principle of ISIT



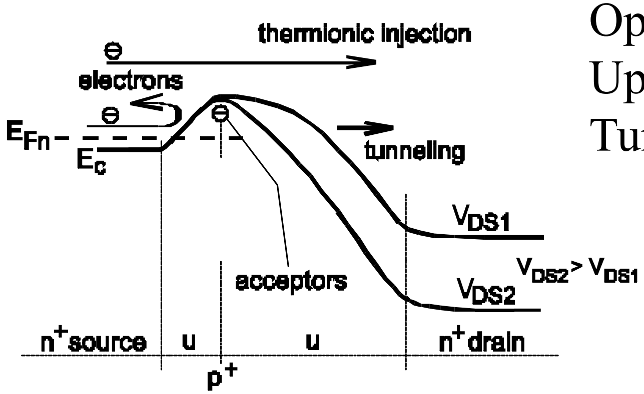
- induced potential barrier
- gate: homojunction or heterojunction or MIS
- potential barrier modulated with gate potential but also with drain potential



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

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

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

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

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

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

•**Power devices**
DC(direct current) electric transmission
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)

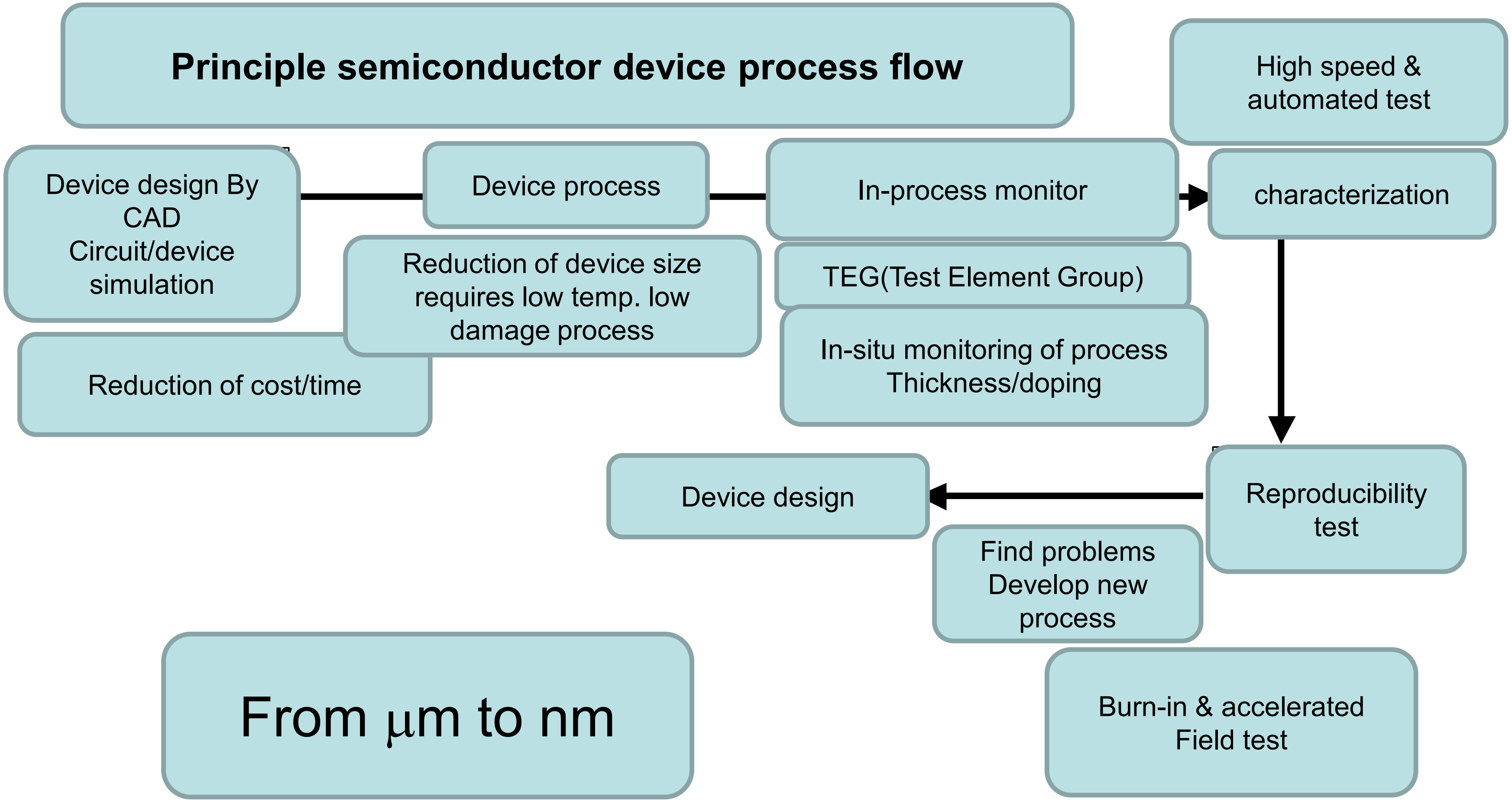
Simple edge emitting LD(stripe LD)
Quantum well LD
Surface emitting LD
(vertical cavity LD)
Quantum cascade LD
Multi-stripe LD(high power)

Light emitting diode (LED)

Indicator
Lighting, illumination

Light detection

Pin, avalanche diode
Quantum well/dot detector


Principle semiconductor device process flow
High speed & automated test
Device design By CAD Circuit/device simulation
Device process
In-process monitor
characterization
Reduction of device size requires low temp. low damage process
TEG(Test Element Group)
In-situ monitoring of process Thickness/doping
Reduction of cost/time
Device design
Reproducibility test
Find problems Develop new process
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

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

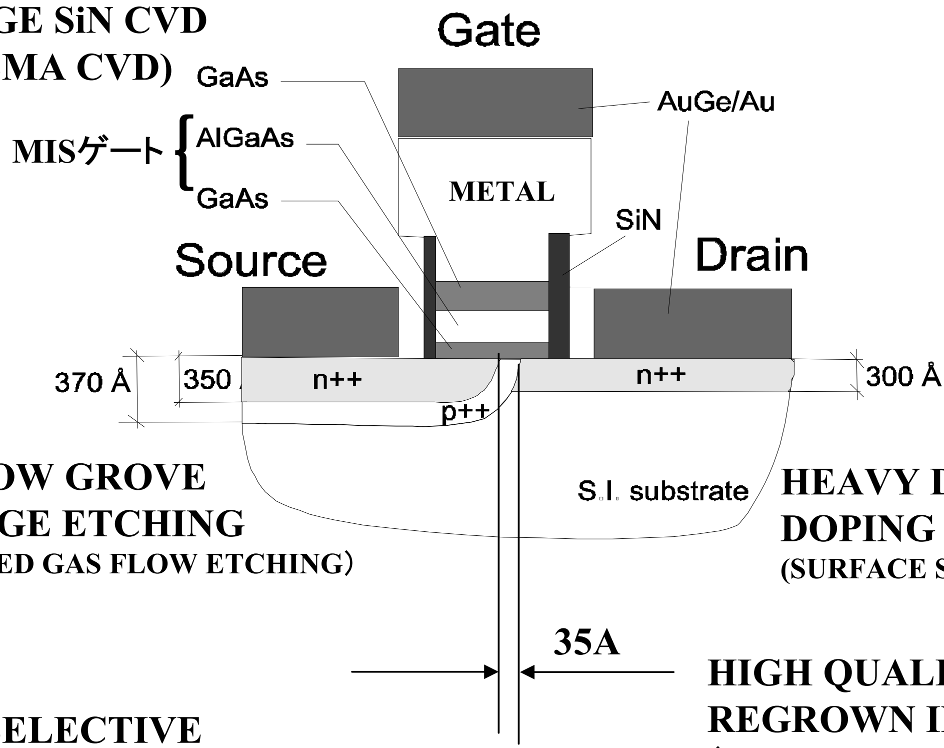
DETAILED CRITICAL PROCESSES FOR ISIT

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）

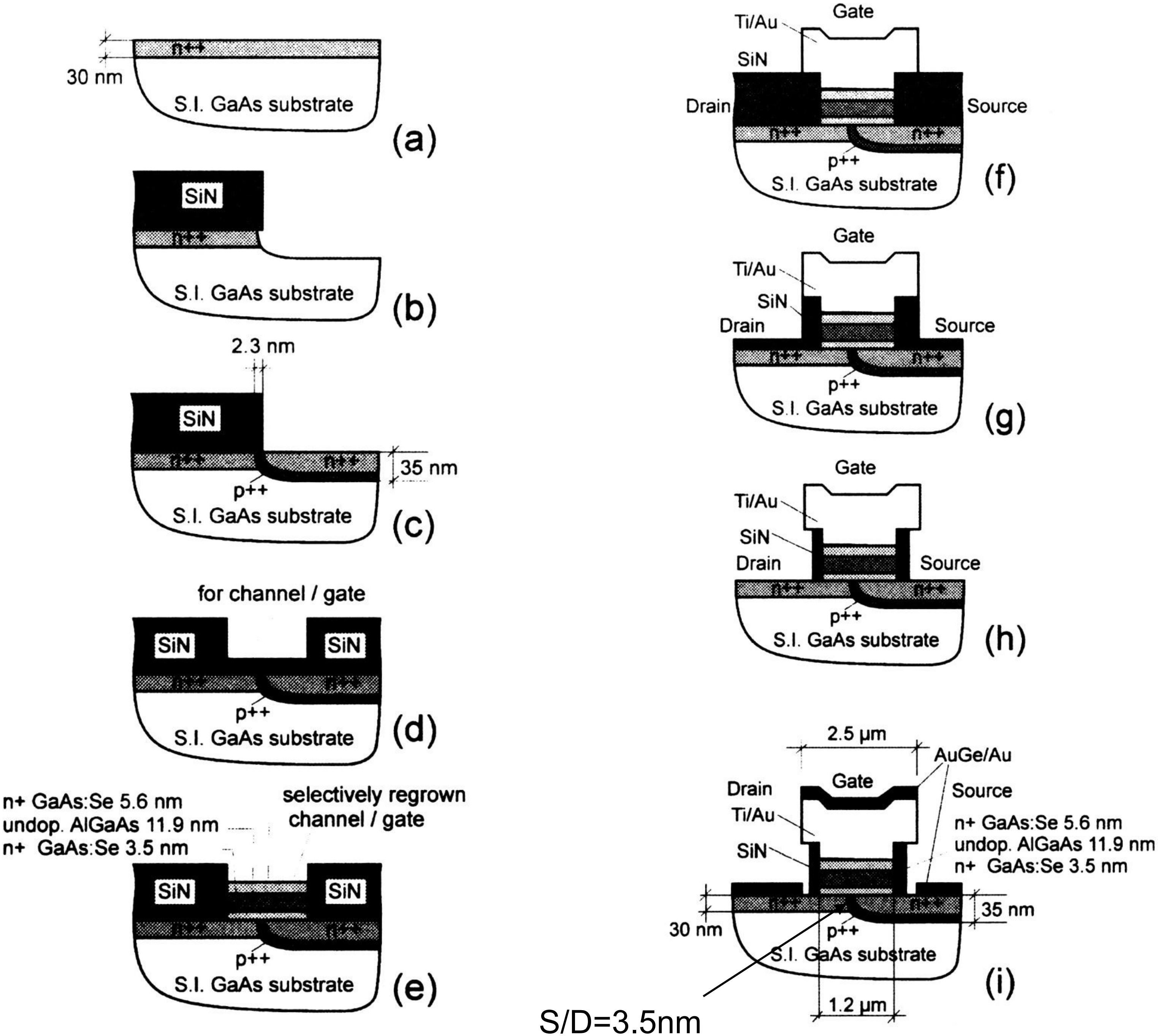


ULTRA SHALLOW GROVE
LOW-T&DAMAGE ETCHING
（PHOTO-STIMULATED GAS FLOW ETCHING）

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
SiN
n+ GaAs:Se 3.5 nm
n++
n++
35 nm
30 nm
p++
S.I. GaAs substrate
(i)
1.2 μm
S/D=3.5nm