カーボンナノサイエンス・ナノテクノロジーの現状と次世代デバイスへの展望

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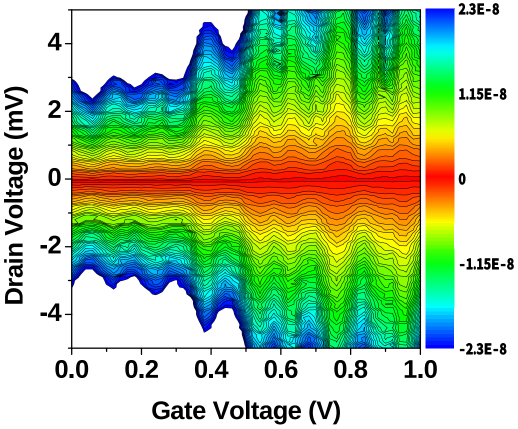
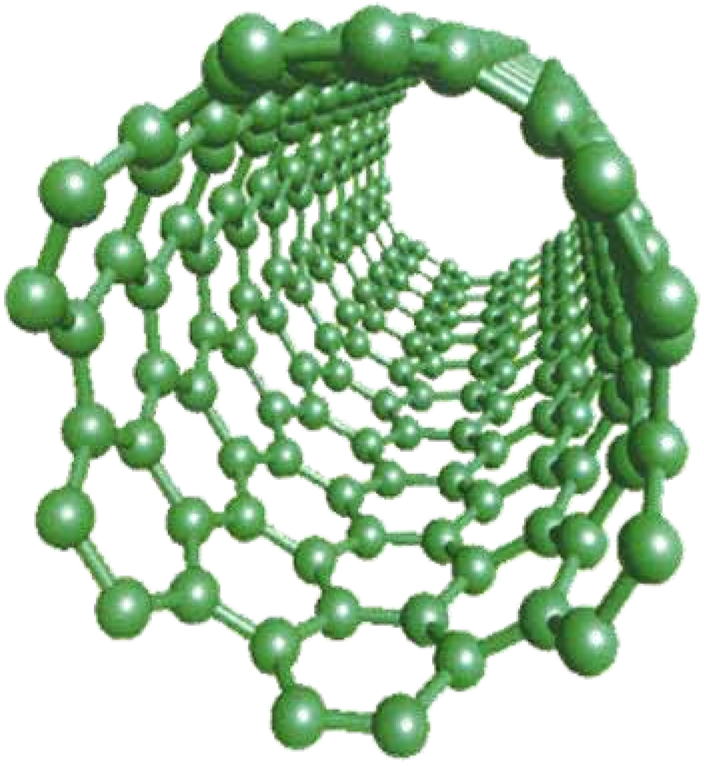




内容

1) カーボンナノチューブの構造

2) カーボンナノチューブの成長とドーピング

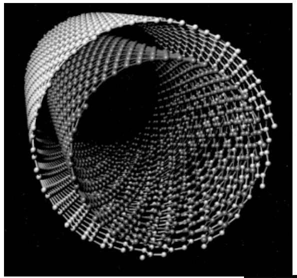
3) トランジスタ応用

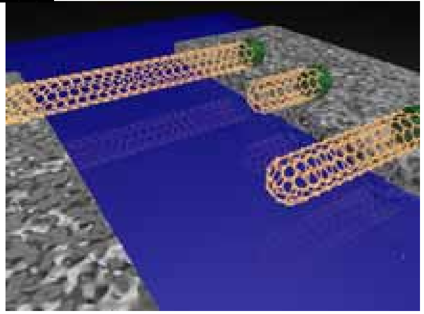
4) 一次元量子伝導

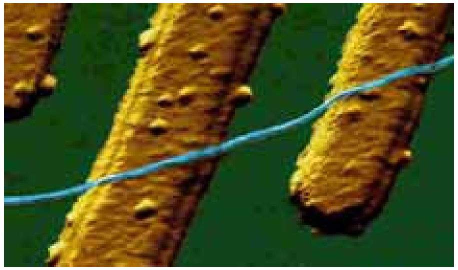
5) コヒーレント伝導

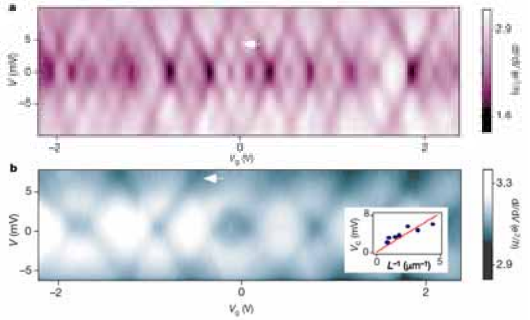
6) 単一電子伝導

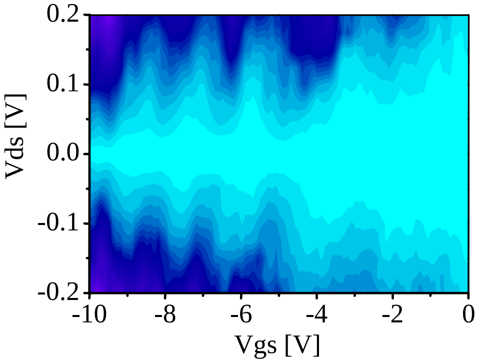
7) その他



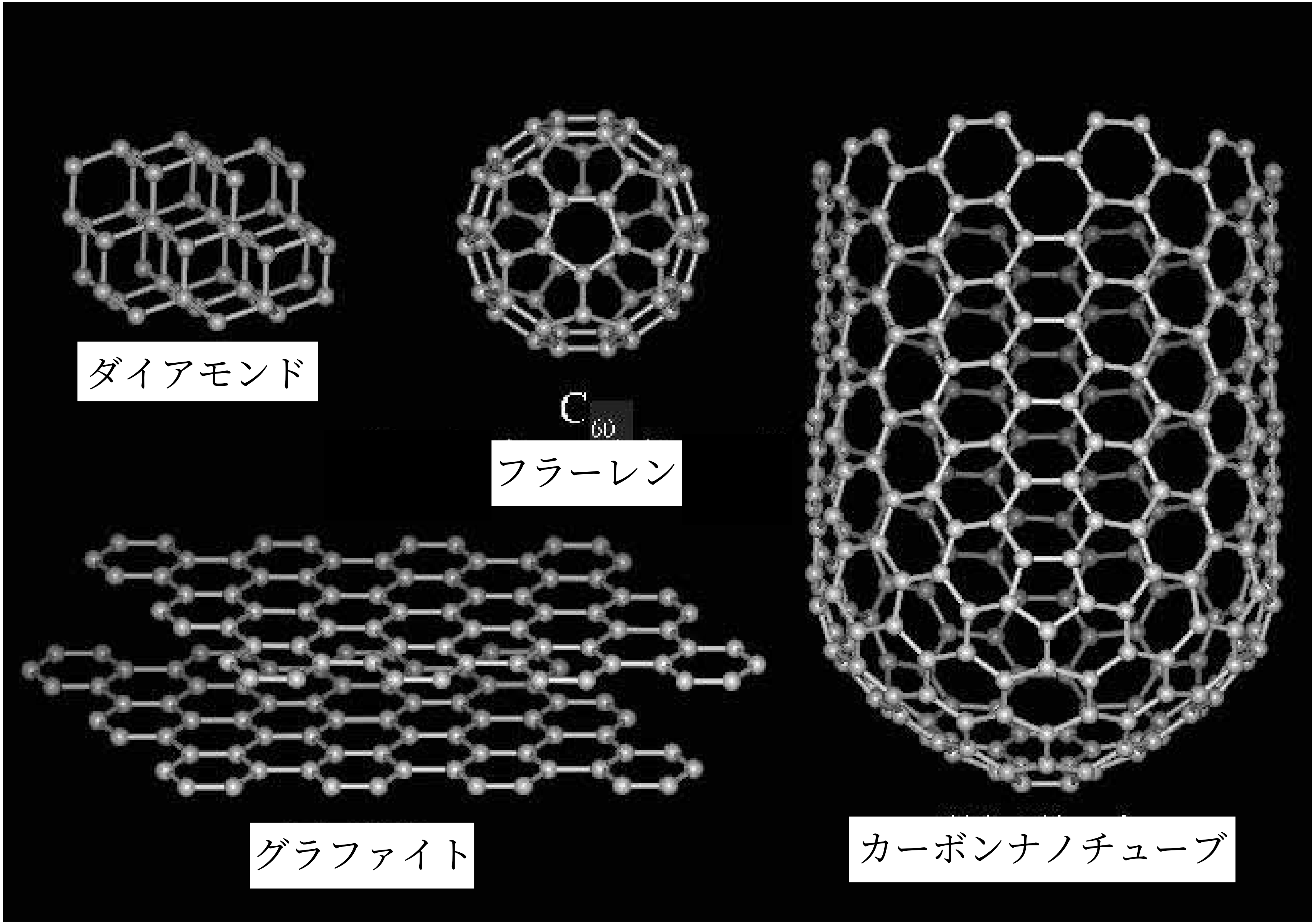




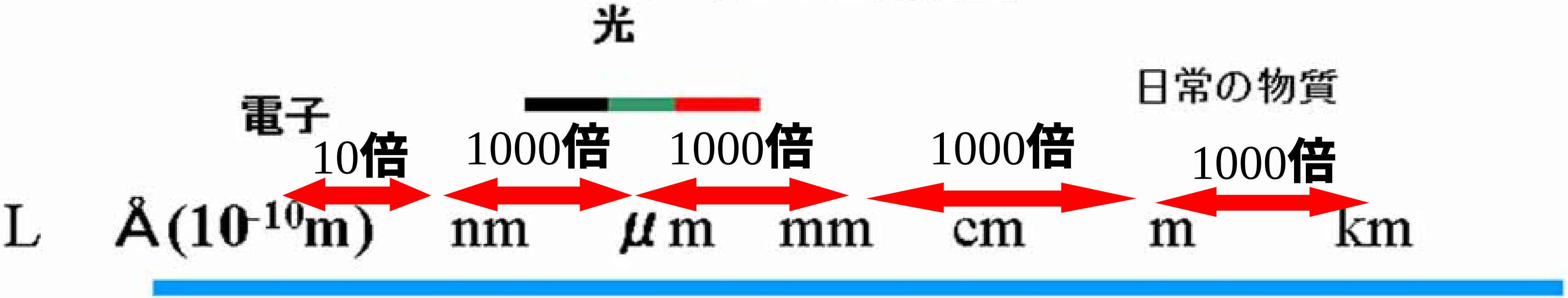




カーボン（炭素）による様々な物質



サイズと物質



光

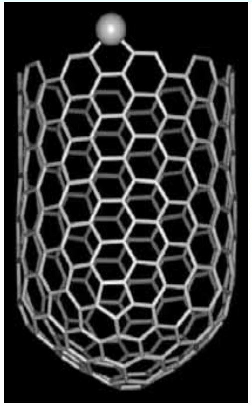
日常の物質

電子

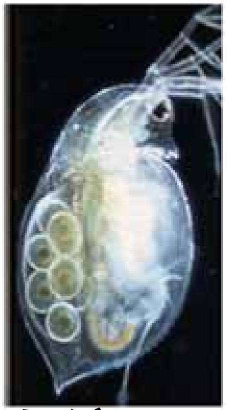
10倍 1000倍 1000倍 1000倍 1000倍

L Å(10^{-10}m) nm μm mm cm m km

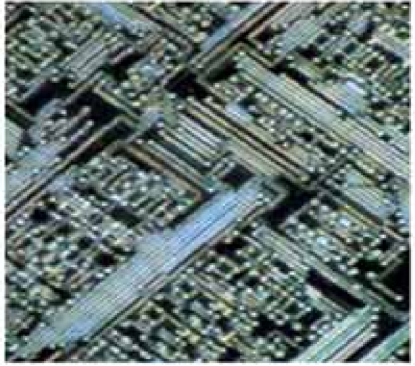
原子



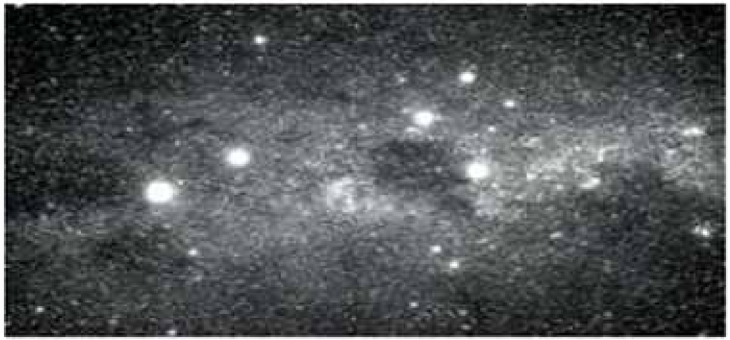
カーボン ナノチューブ



ミジンコ



集積回路 (LSI)



電子顕微鏡の原理

走査型電子顕微鏡

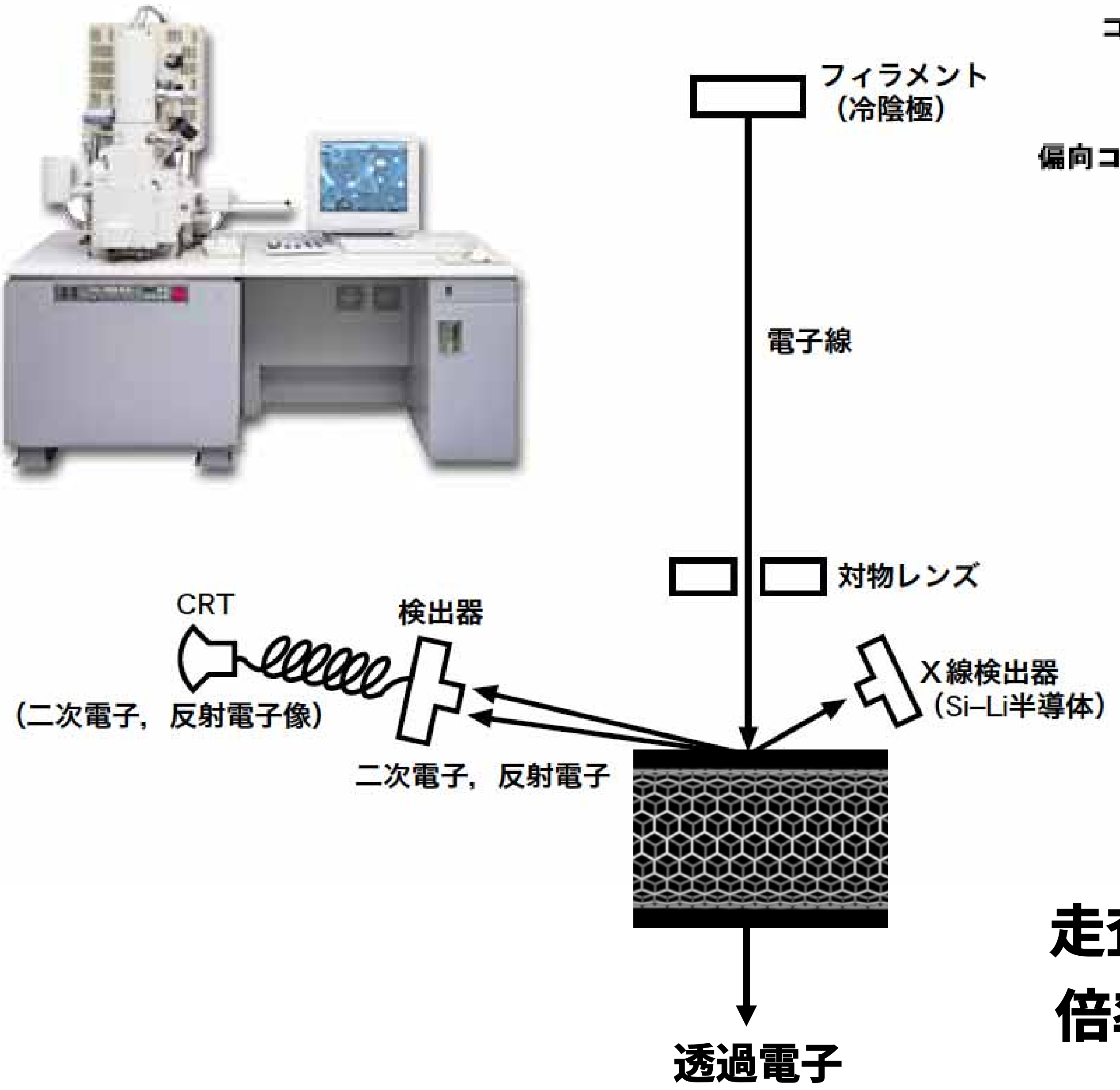
倍率　５０万倍

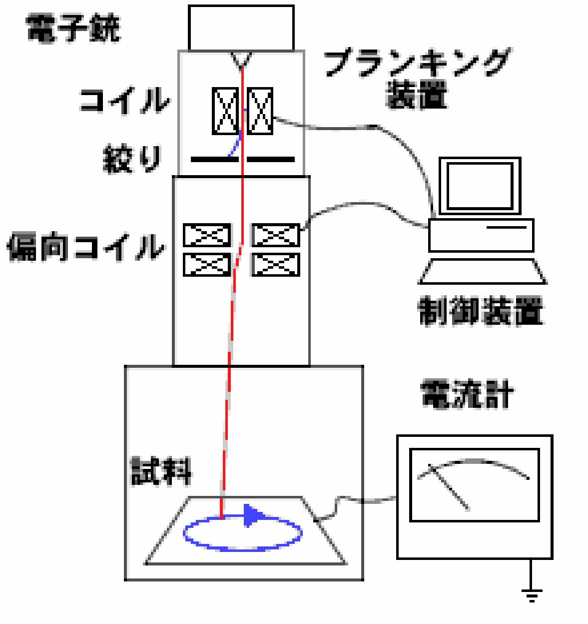
透過型電子顕微鏡

倍率　～２００万倍

光学顕微鏡→倍率３０００倍

電子顕微鏡の原理

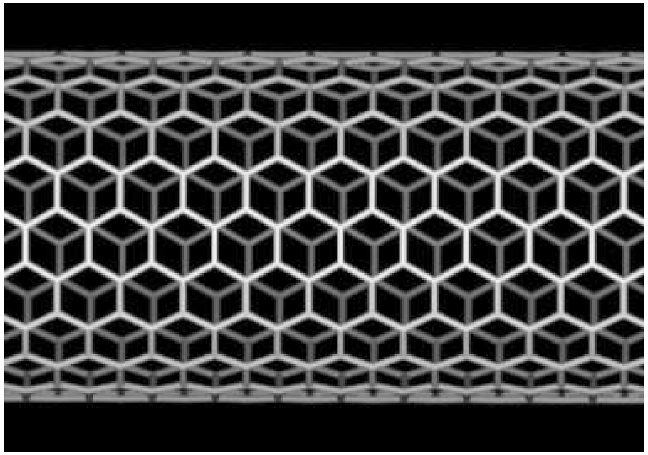


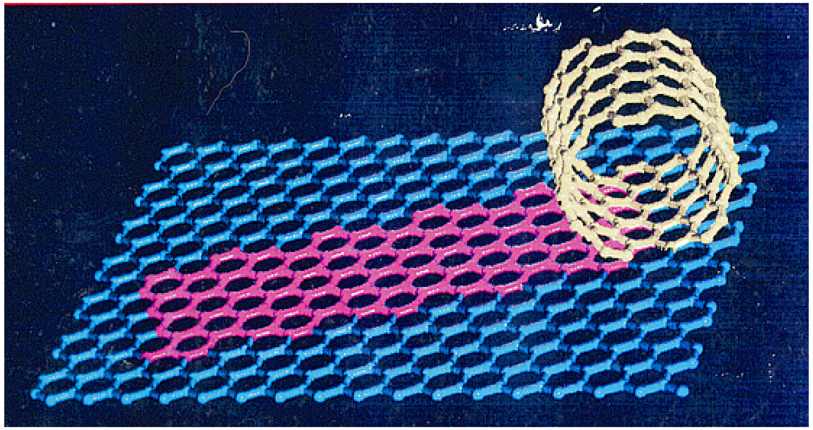


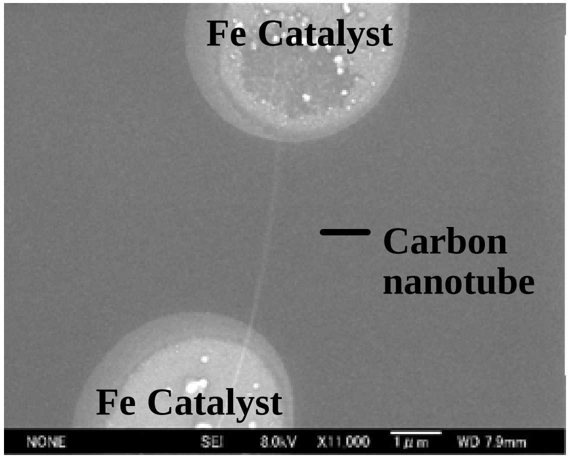
走査型電子顕微鏡

倍率　１００万倍

単層カーボンナノチューブの構造



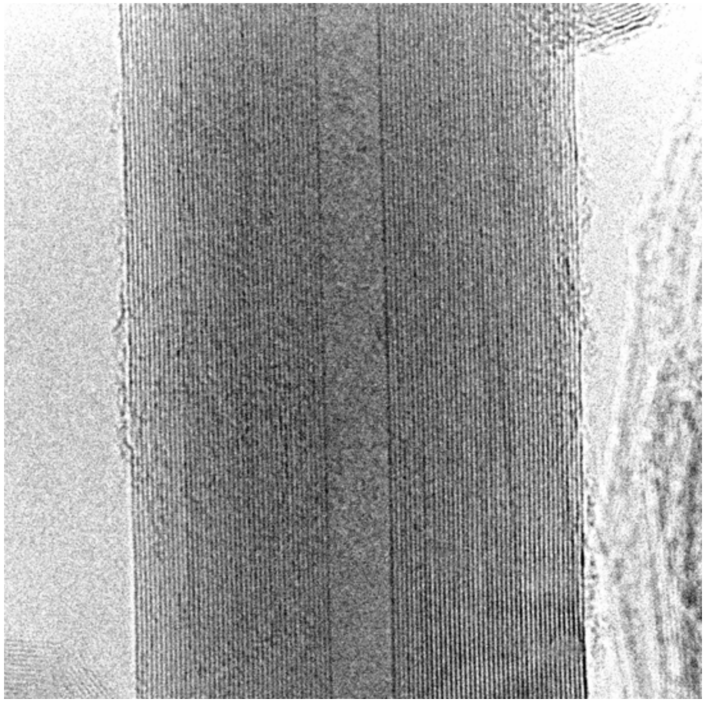




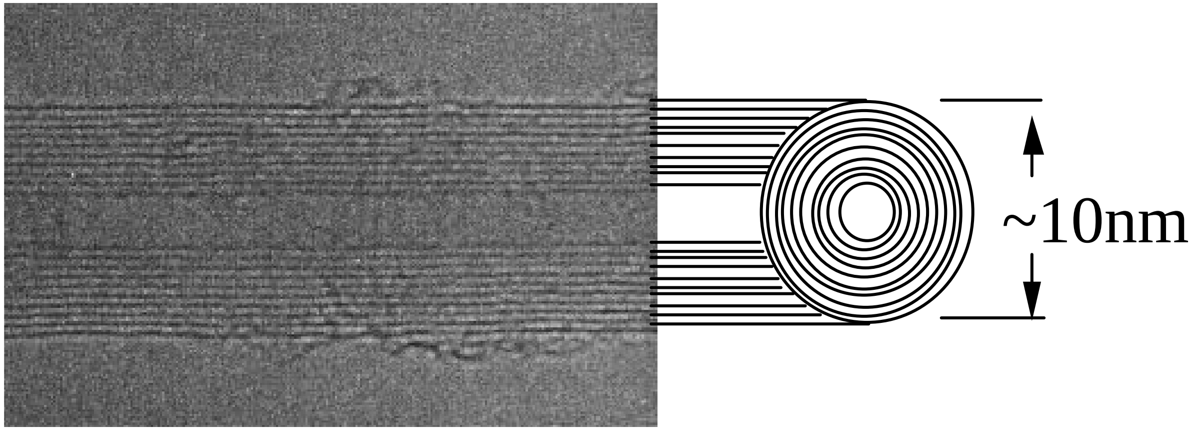
走査型電子顕微鏡で観察した
単層カーボンナノチューブ

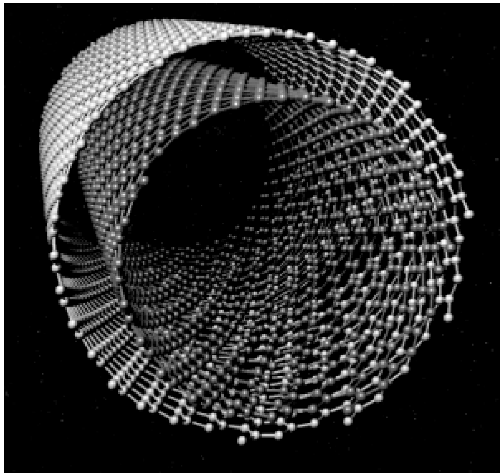
透過型電子顕微鏡で観察した
単層カーボンナノチューブ

多層カーボンナノチューブ



多層カーボンナノチューブの
透過型電子顕微鏡写真

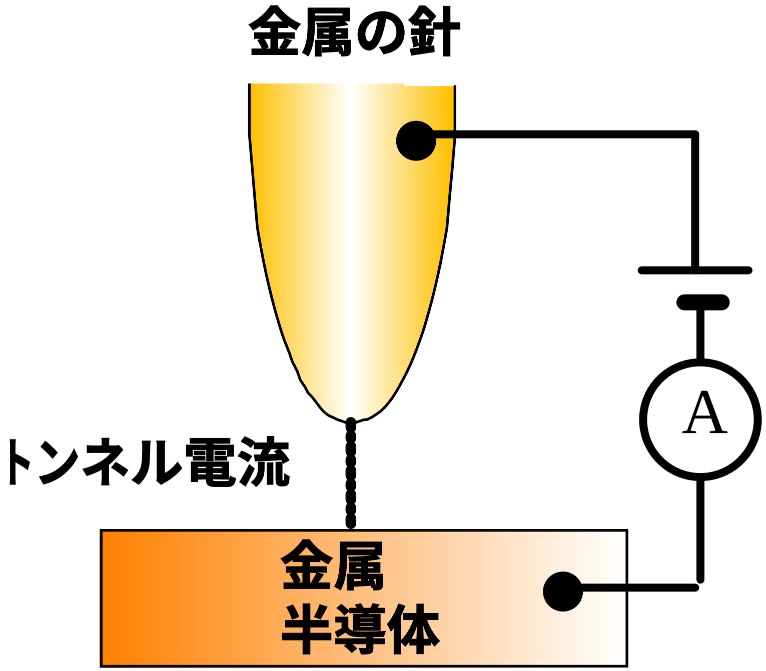


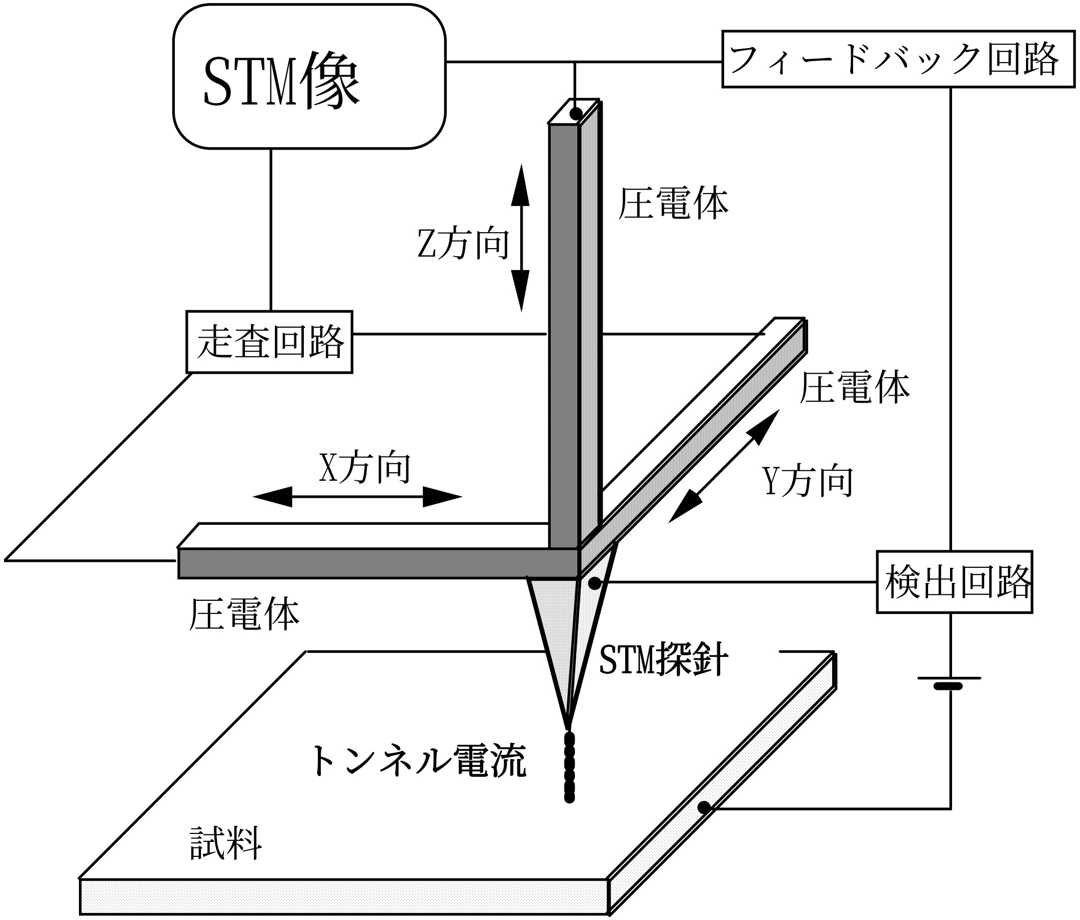


層間距離 0.34nm

層数制御 不可能

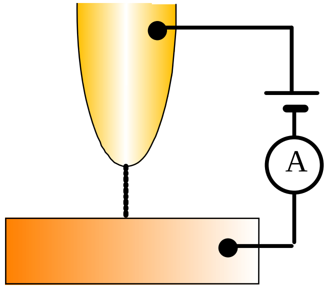
走査型トンネル顕微鏡
Scanning Tunneling Microscope (STM)



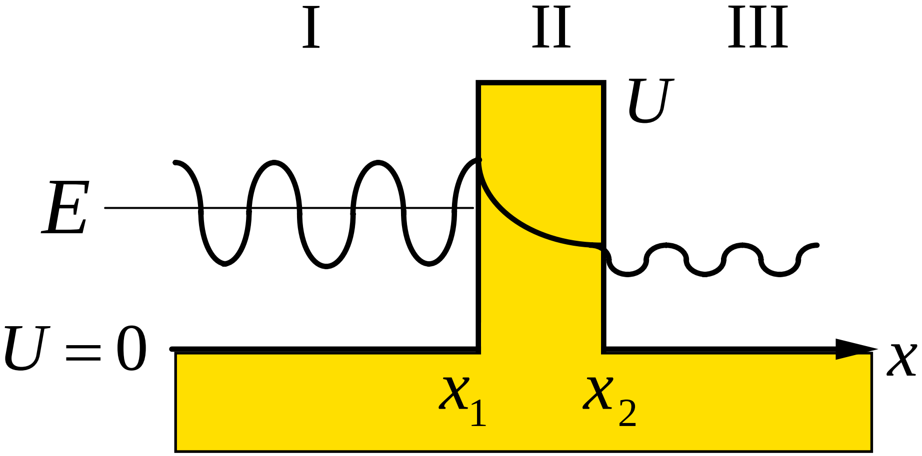


IBM **スイス チューリッヒ研究所**
・ビーニッヒ／ローラー

トンネル効果



電子の波としての性質
障壁の中で減衰



1）ポテンシャル障壁が薄いほど

2）ポテンシャル障壁が低いほど

トンネルしやすい

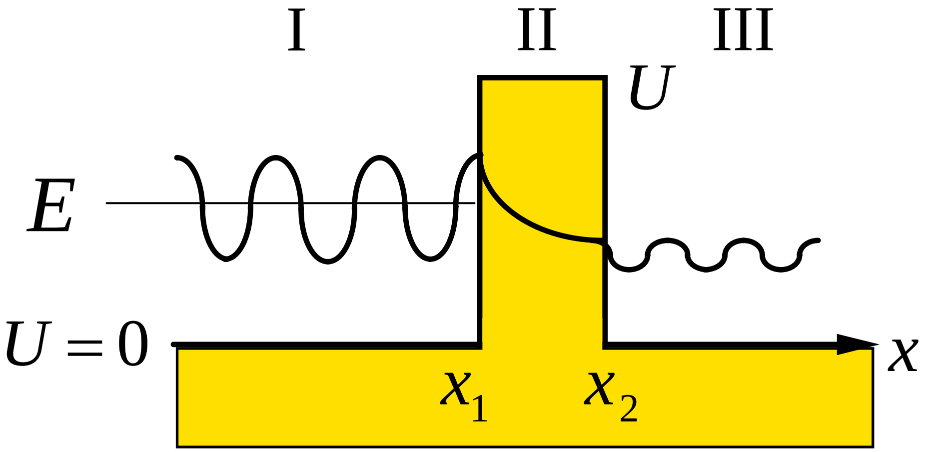
シュレーディンガー方程式

$$-\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2}+U(x)=E\varphi$$

透過確率

$$T\approx\exp\left[\frac{-2}{\hbar}\int_{x_1}^{x_2}\sqrt{2m(E-U)}\,dx\right]$$

透過係数

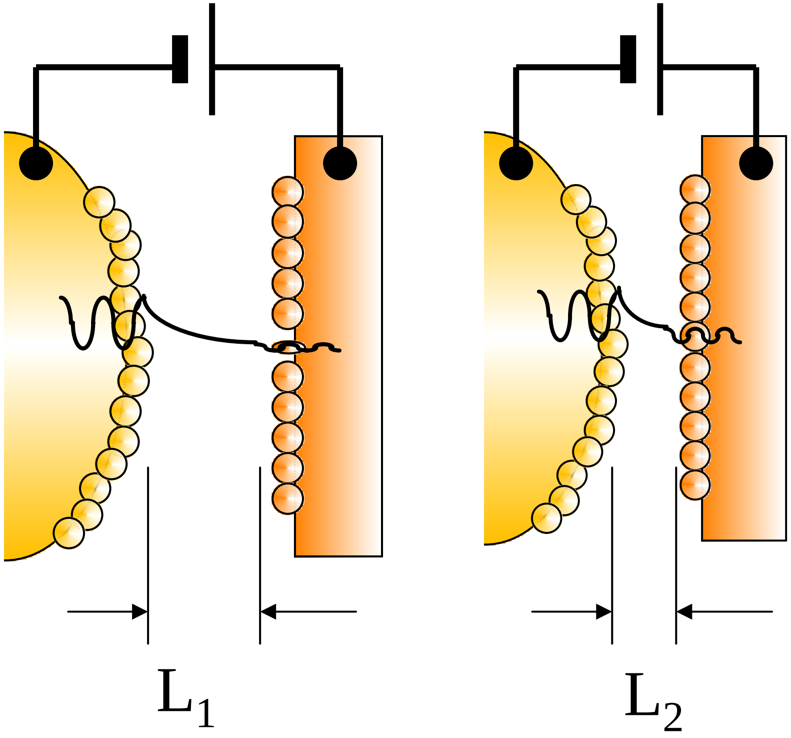


$$\varphi = A\exp\left(\frac{\pm i}{\hbar}\int_{x_0}^{x}\sqrt{2m(E-U)}dx\right)$$

透過係数 $T = \left|\frac{\varphi(III)}{\varphi(I)}\right|^2$

$$T \approx \exp\left[\frac{-2}{\hbar}\int_{x_1}^{x_2}\sqrt{2m(E-U)}dx\right]$$

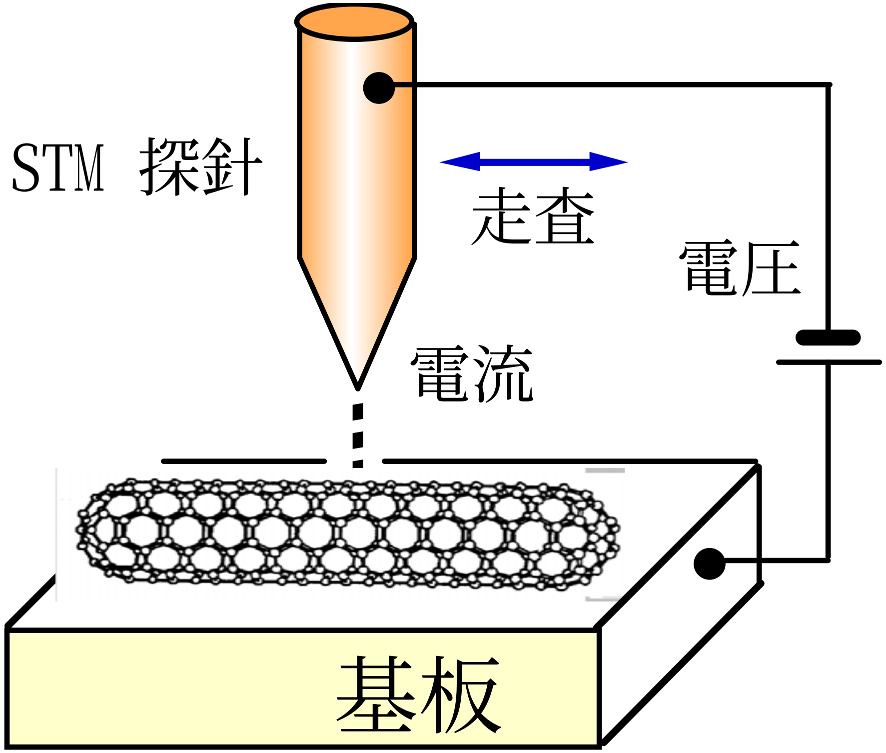
$L_1 > L_2$ → $T_1 << T_2$

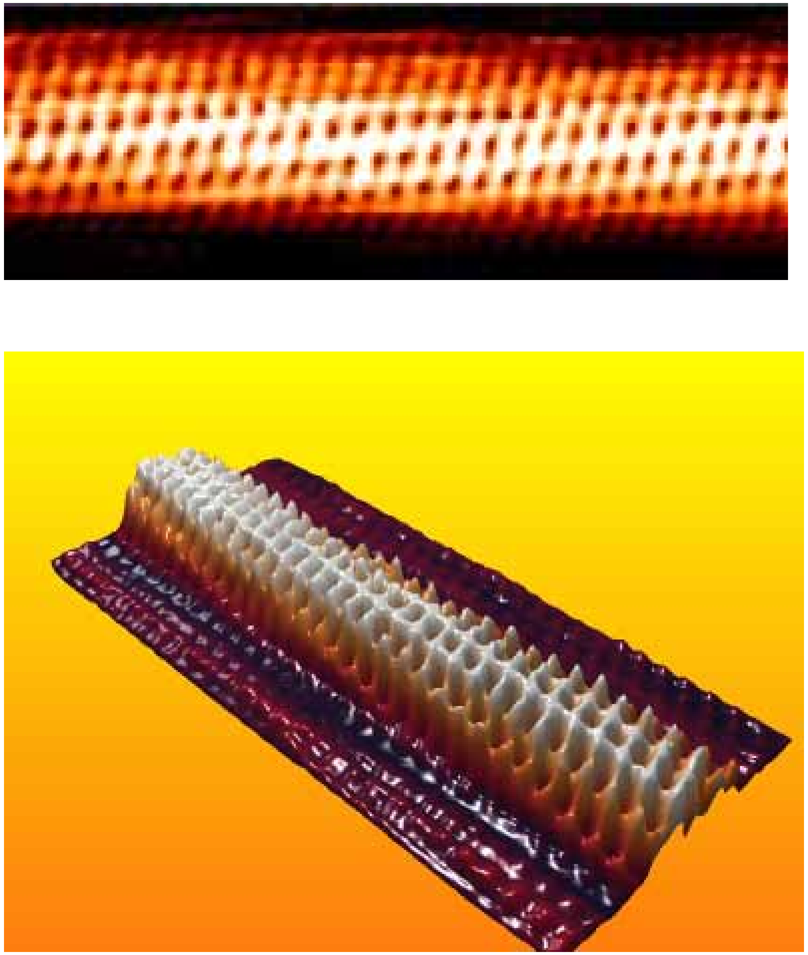


STMにおいて

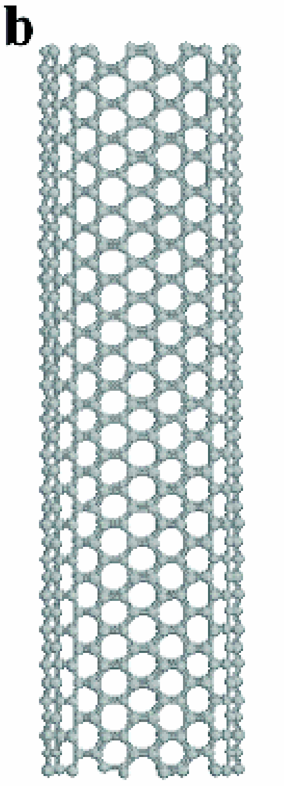
L：1Å **大きくなる**
T：10**倍小さくなる**

走査型トンネル顕微鏡で観察したカーボンナノチューブ



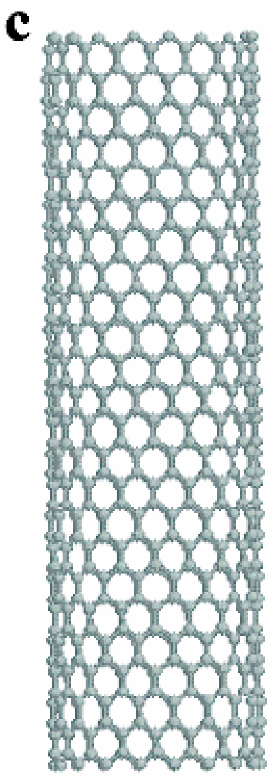


Chirality of Carbon Nanotube
カイラリティー



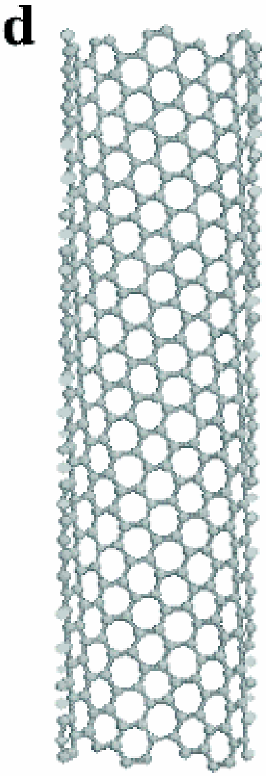
armchair

- Metal



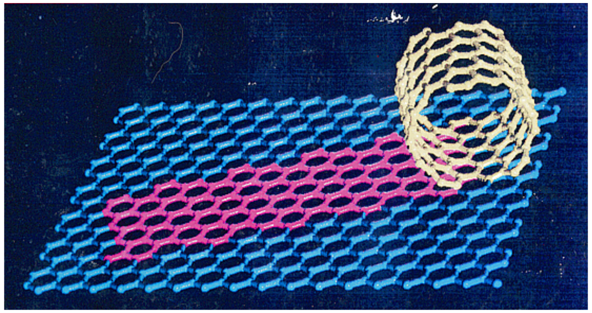
zigzag

- Metal
- Semi Con.



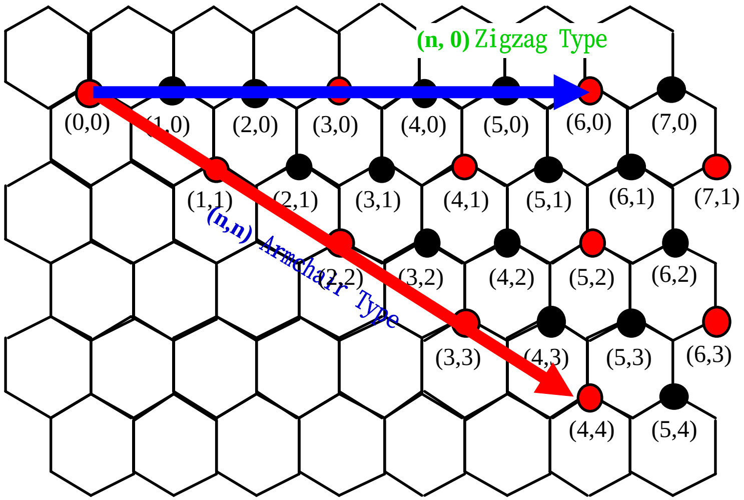
chiral

- Metal
- Semi Con.

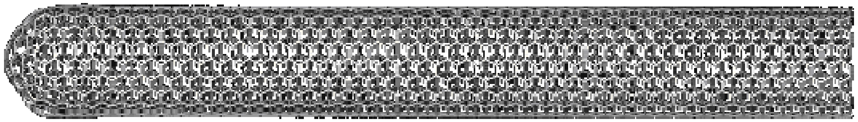


● 1/3 Metalic

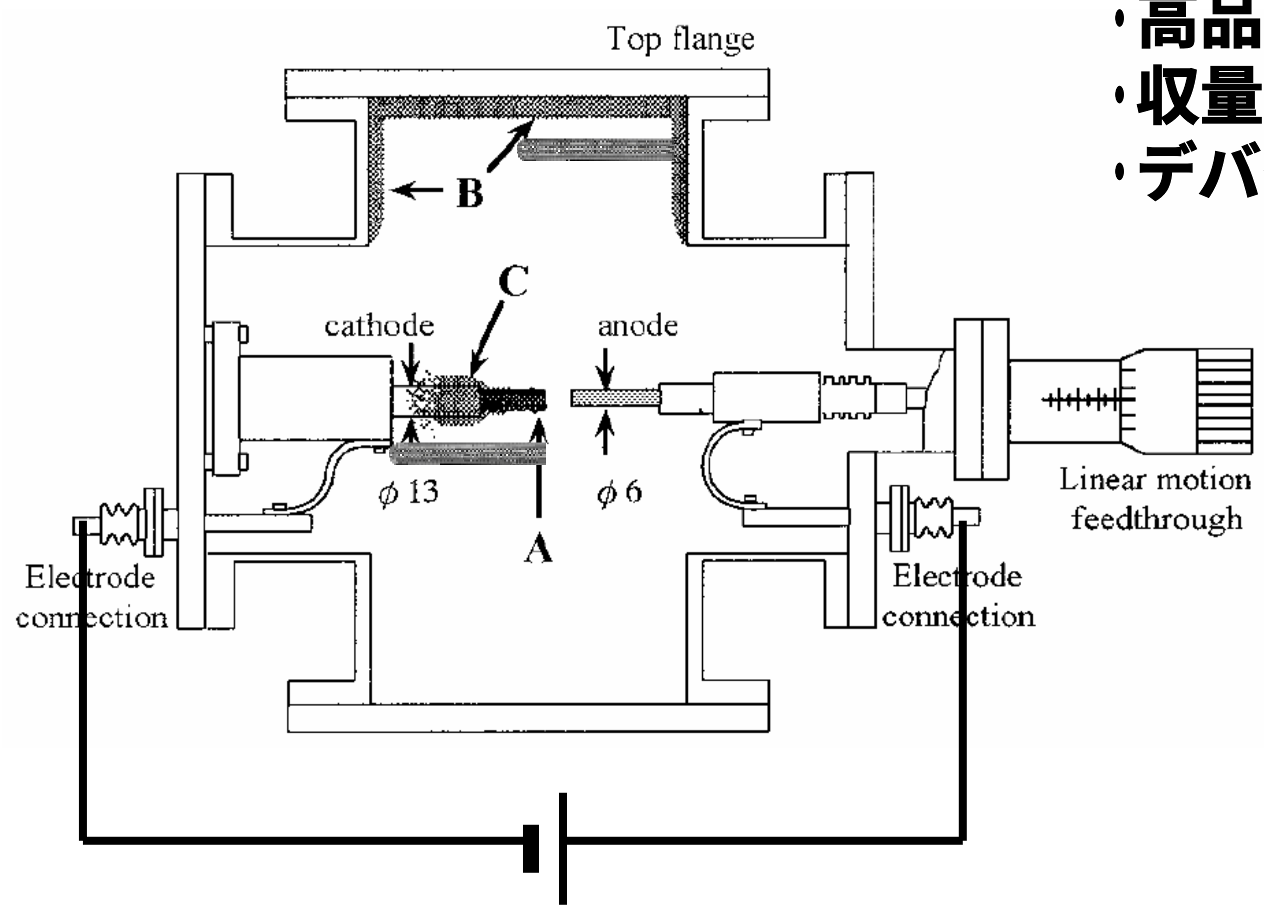
● 2/3 Semiconductor



カーボナノチューブの
アーク放電成長法



- 高品質 (欠陥少)
- 収量　少
- デバイスに不向き

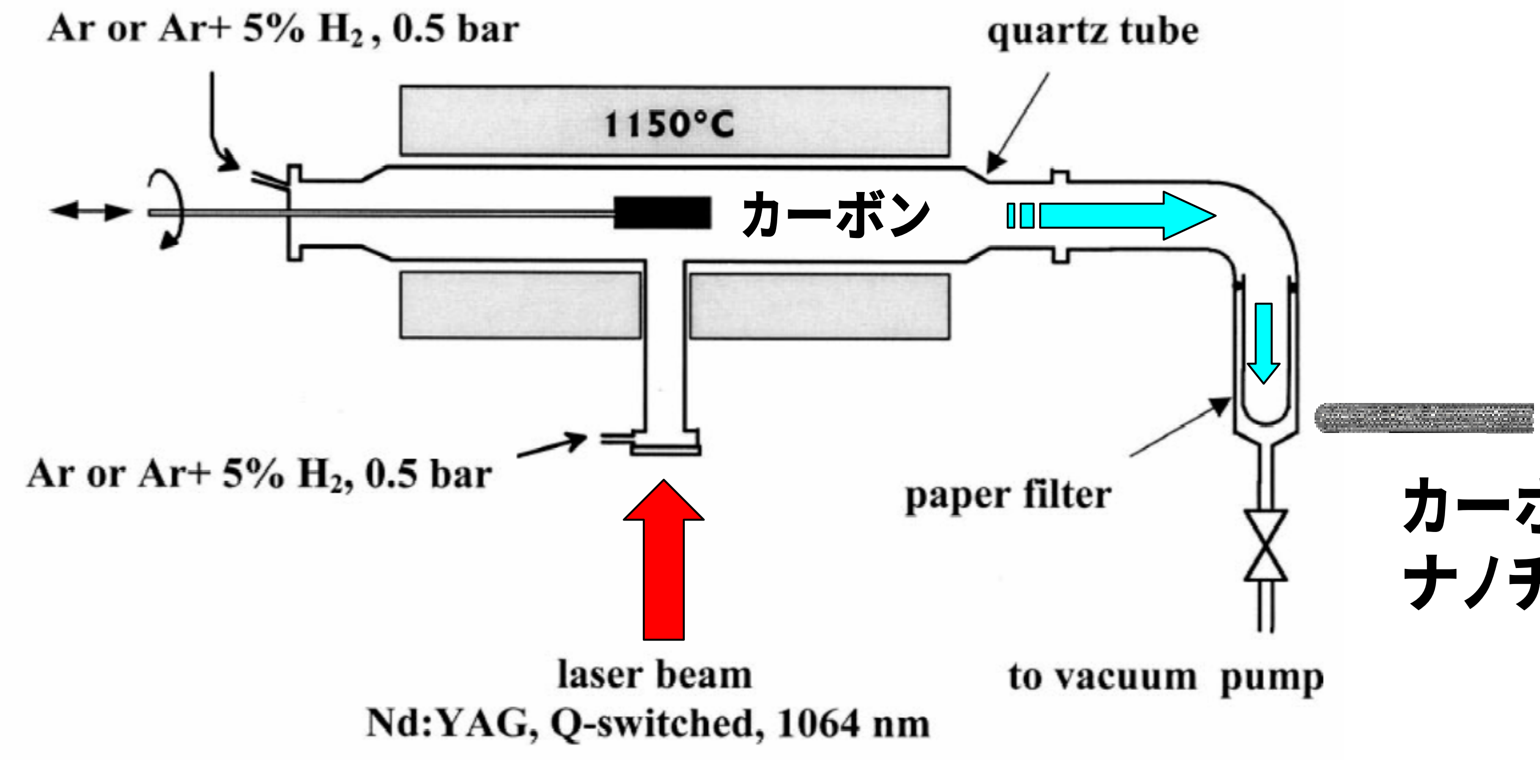


高電圧

カーボンナノチューブの レーザーアブレーション成長法

昇華

- 品質普通
- 収量　大
- デバイスに不向き



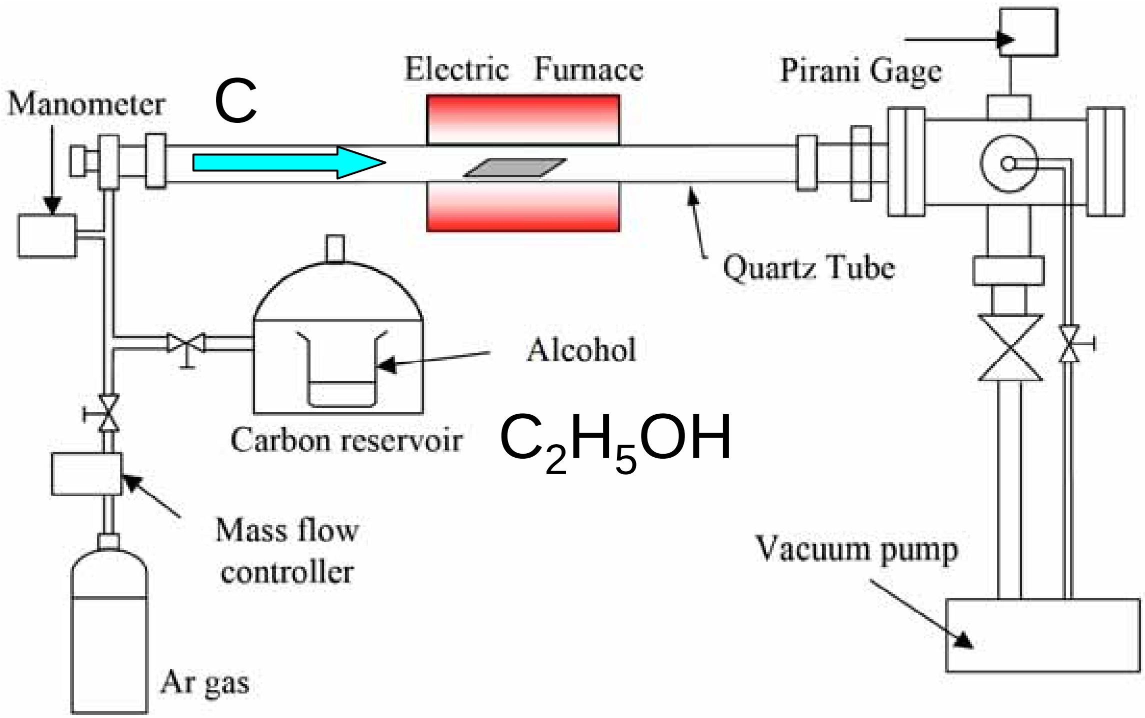
カーボン

カーボン
ナノチューブ

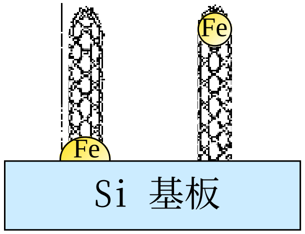
カーボナノチューブの化学気相成長法 (CVD)

Chemical Vapor Deposition (CVD)

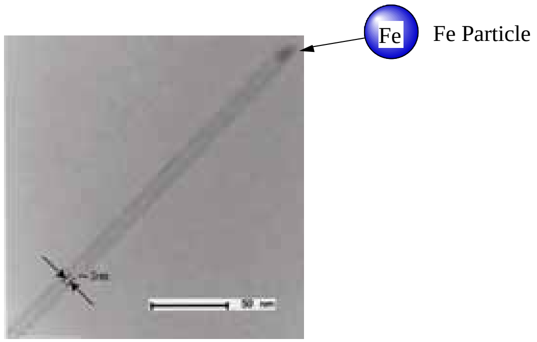
- 品質やや悪い
- 収量　普通
- デバイスに最適



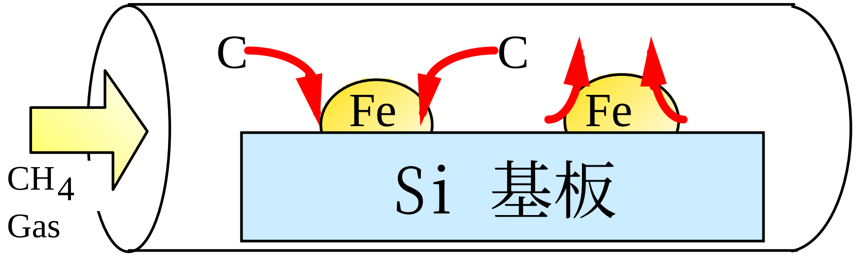
C_2H_5OH



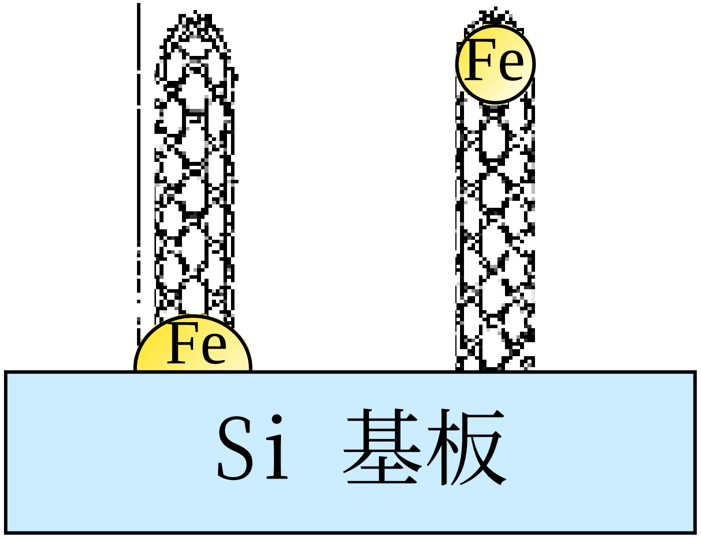
カーボンナノチューブの鉄触媒からの化学気相成長方法



TEM Image of SWCNT



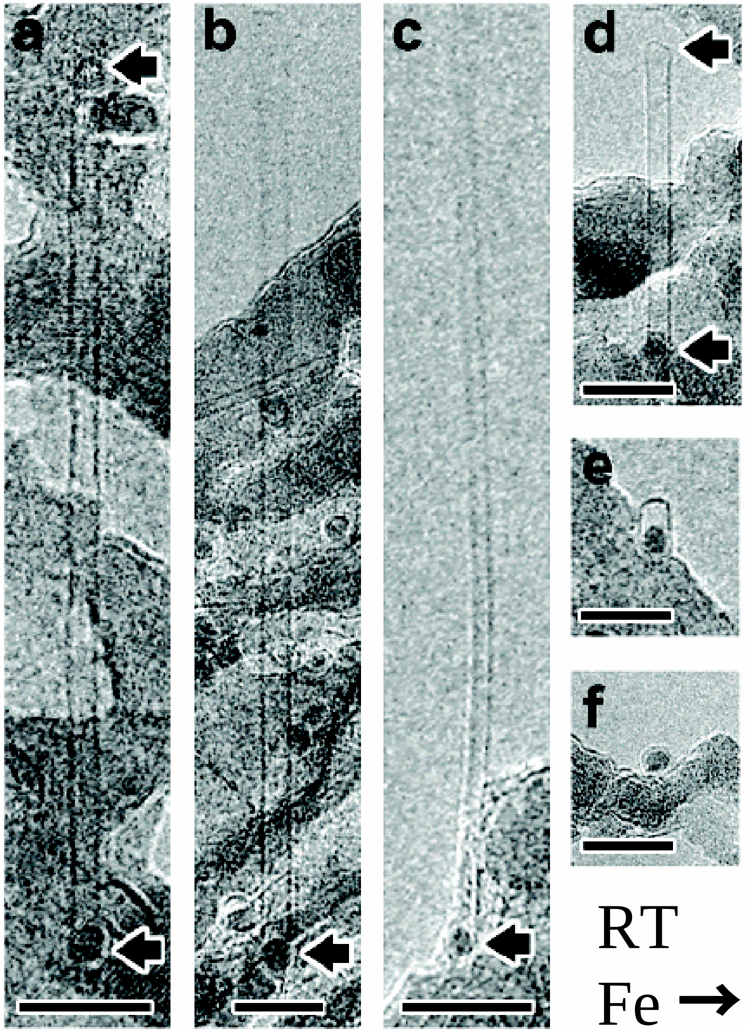
900C/30min.



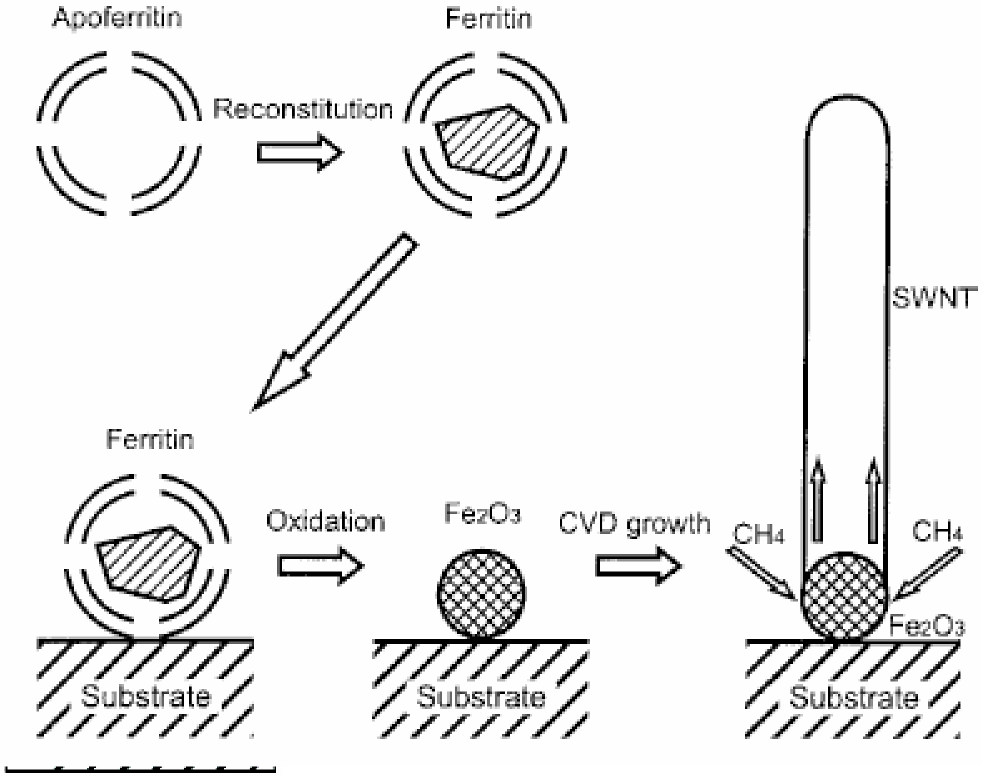
- **鉄** (Fe) **の微粒子 → 触媒**
- **炭素ガスから触媒を経由**
- **カーボンナノチューブが成長**

- **鉄触媒　先端に残る場合**
- **鉄触媒　根元に残る場合**

Carbon Nanotube Growth from Fe Particles



SCHEME 1. Process Flow for SWNT Synthesis from Discrete Nanoparticles by CVD



RT Heating CVD

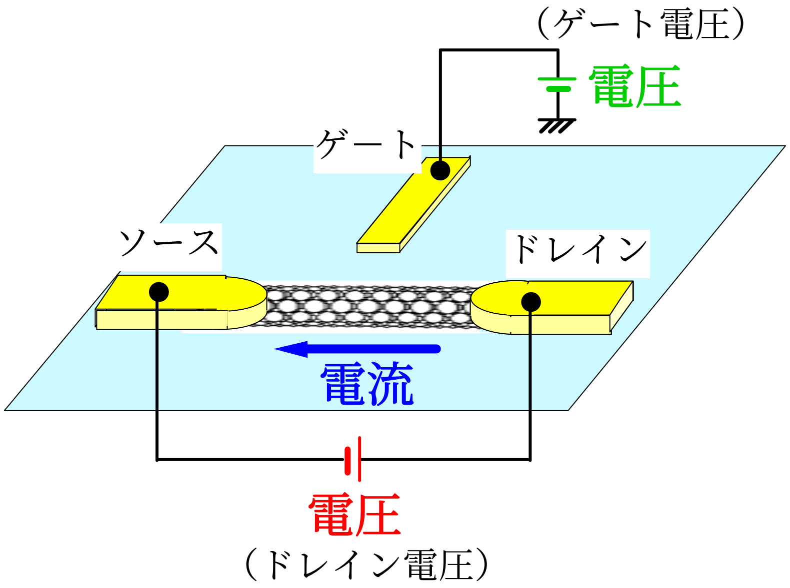
Fe → Fe_3O_4 → Fe_2O_3 → Fe_3O_4 → Fe-C → CNT

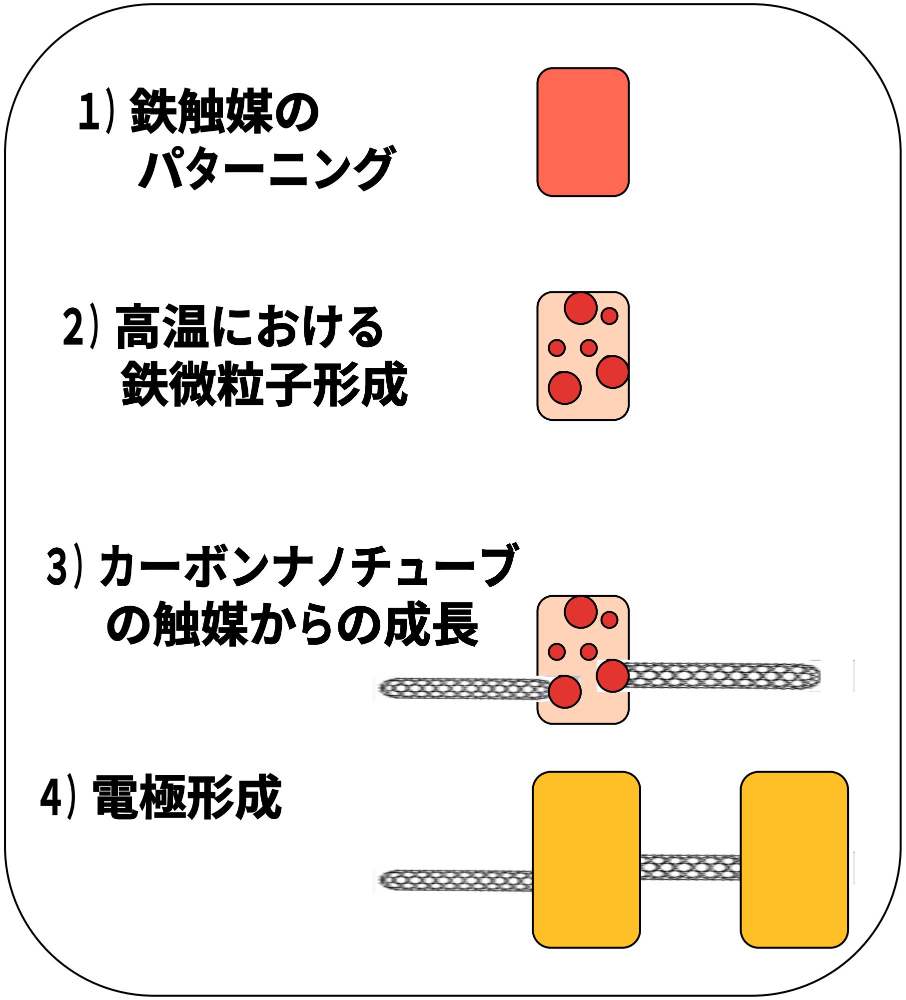
FeO

Fe_3C

Fe-C

カーボンナノチューブ電子デバイス





1) **鉄触媒のパターニング**

2) **高温における鉄微粒子形成**

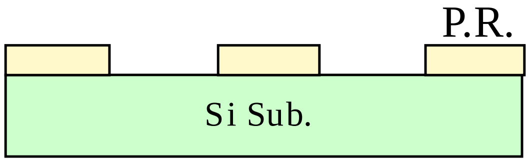
3) **カーボンナノチューブの触媒からの成長**

4) **電極形成**

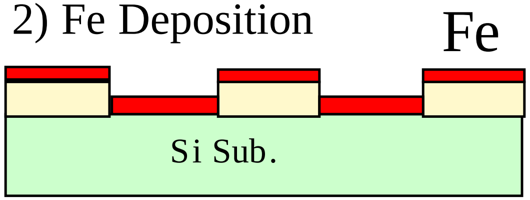
問題点：1) 方向　2) 本数　3) 直径　4) 位置　5) カイラリティー

Position Controlled Growth of Carbon Nanotube using Patterned Catalyst

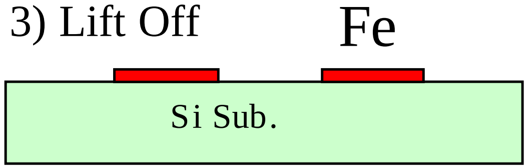
1) Photo Resist Patterning



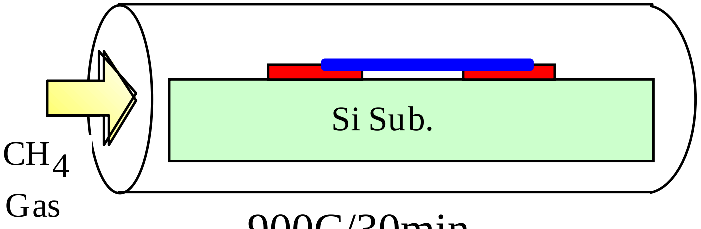
2) Fe Deposition



3) Lift Off



4) Carbon Nanotube Growth



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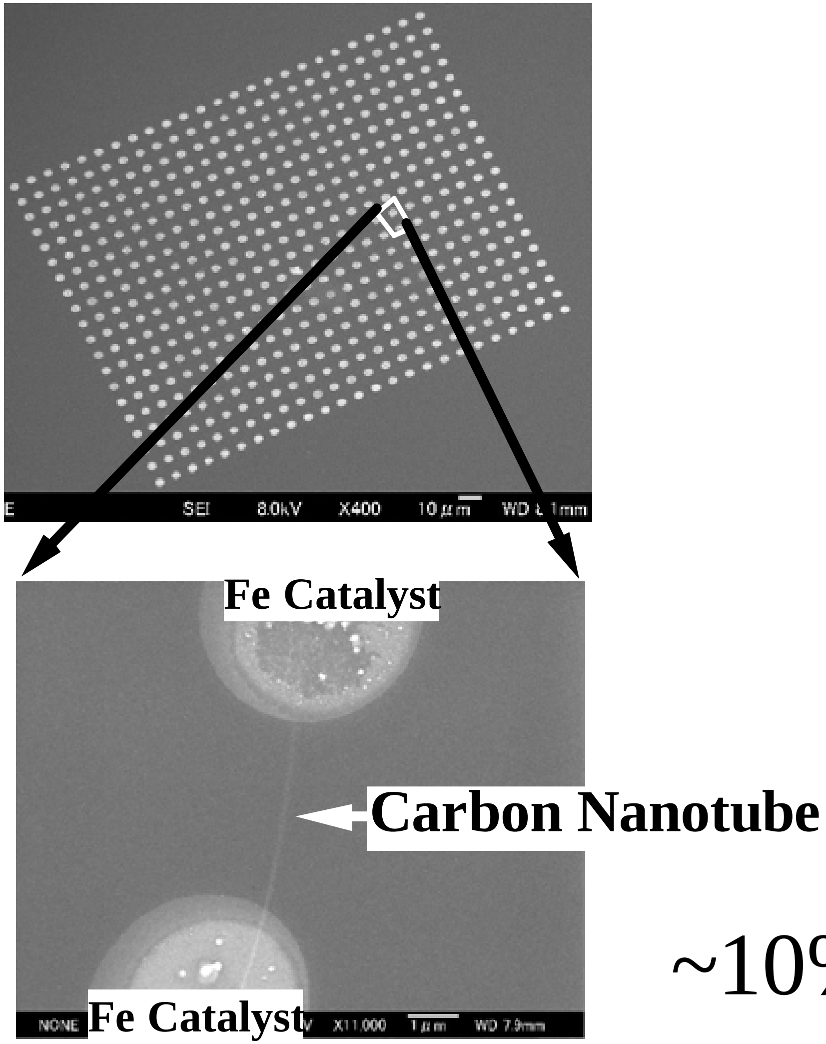
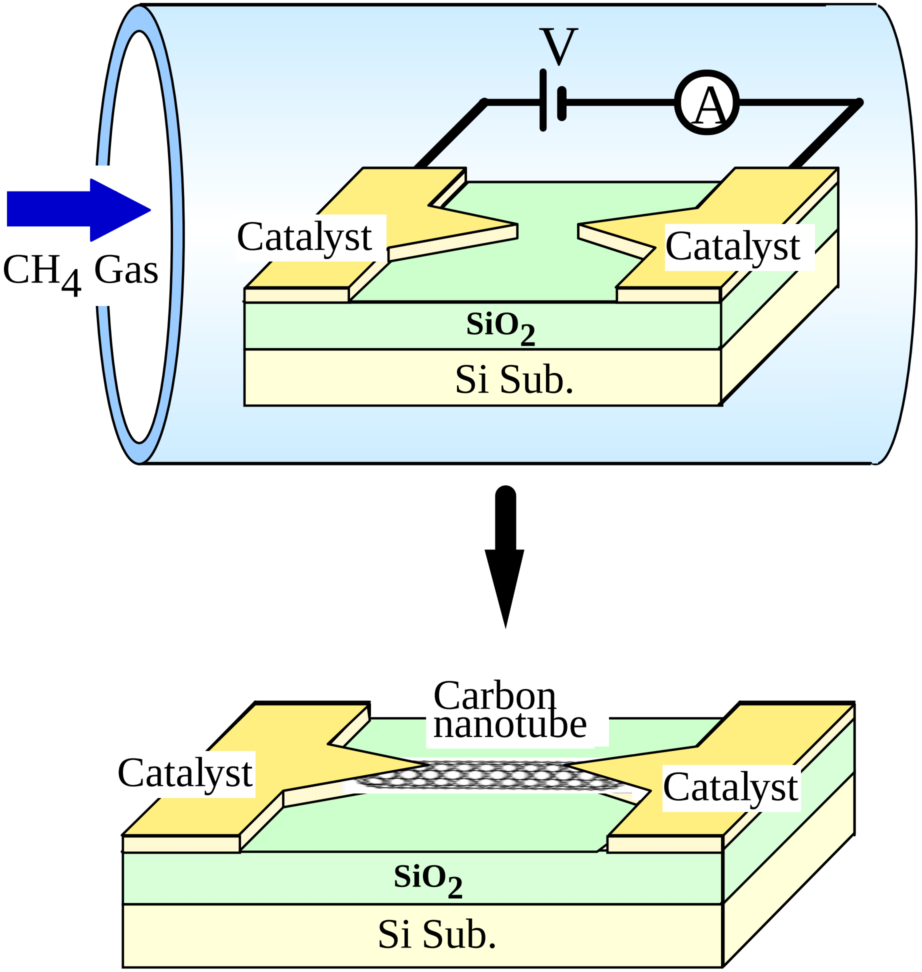
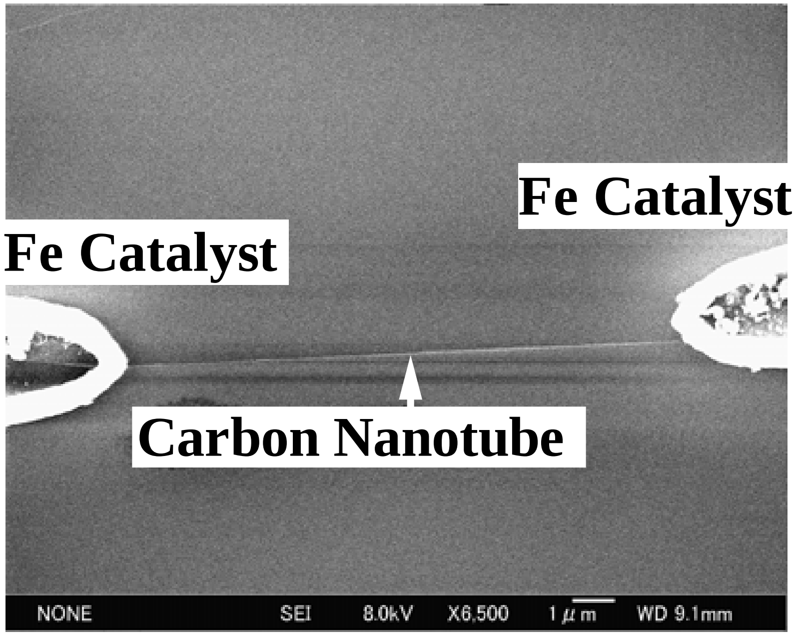


~10%

電界印加成長によるカーボンナノチューブの方向制御

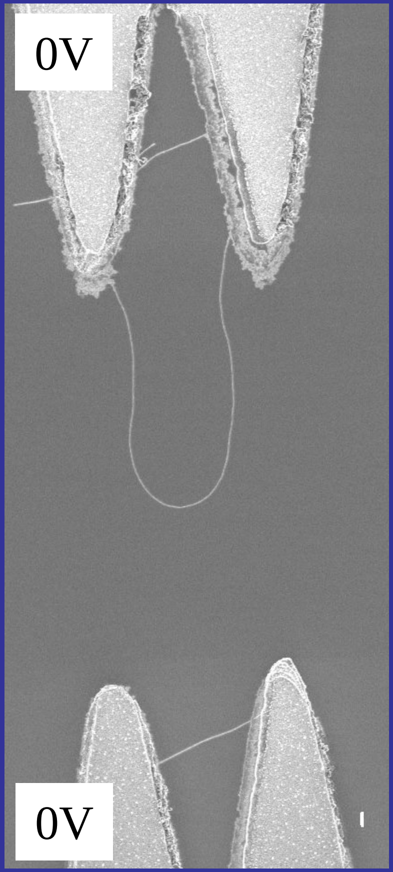




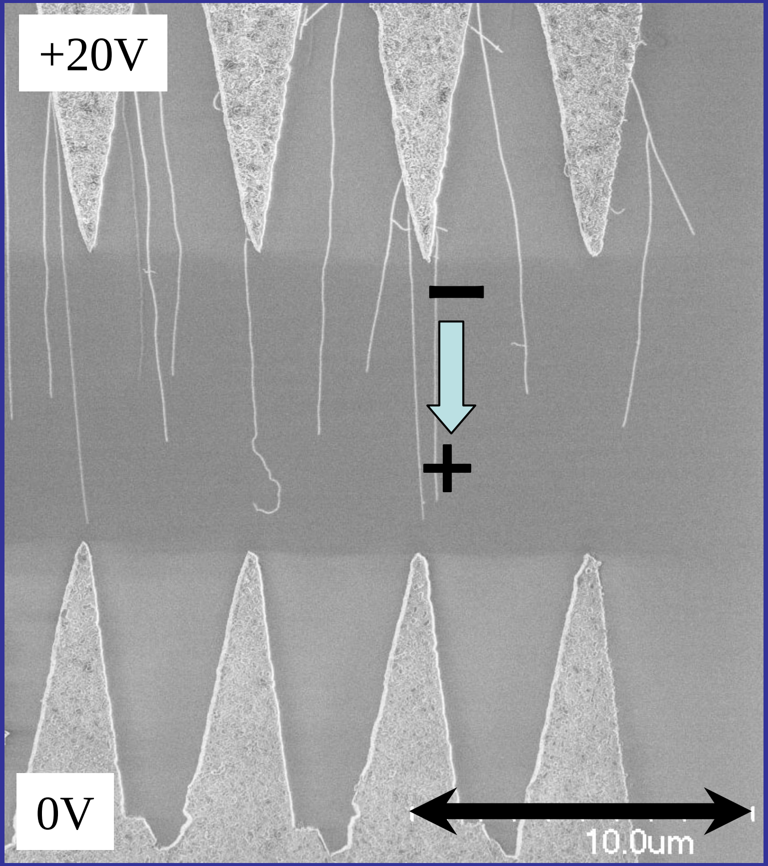
~20%

Effect of Van der Waals Force
between Carbon Nanotube & SiO_2 Sub.

電界印加成長によるカーボンナノチューブの方向制御

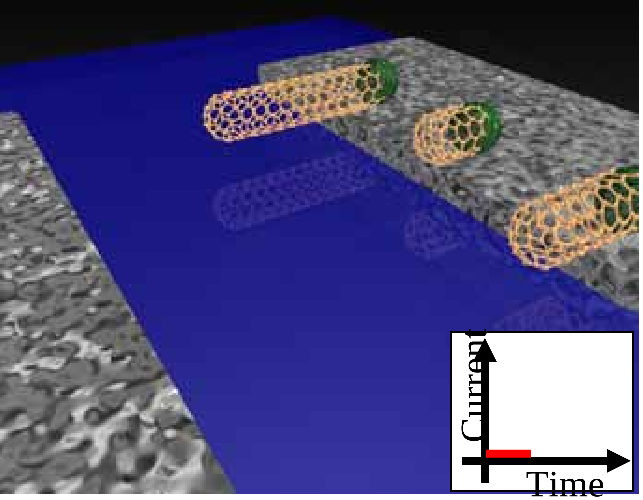


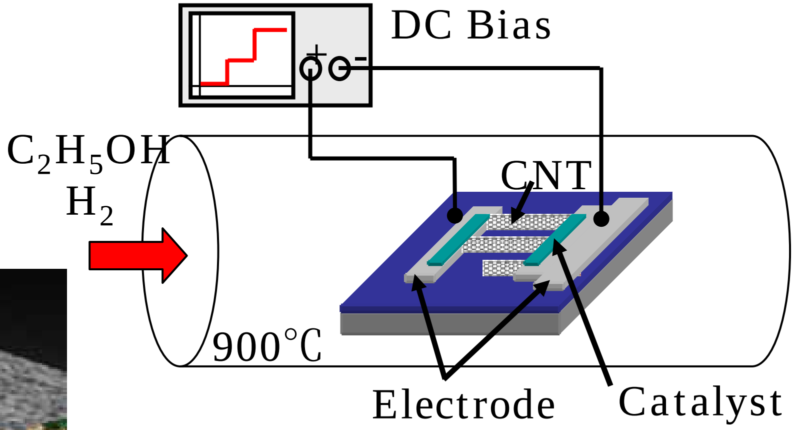
Growth without Electric field

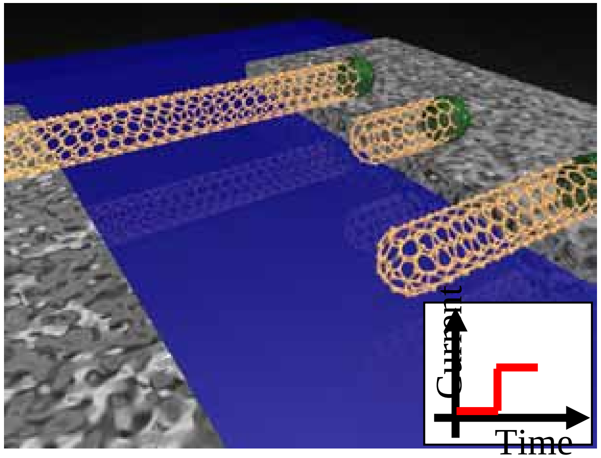


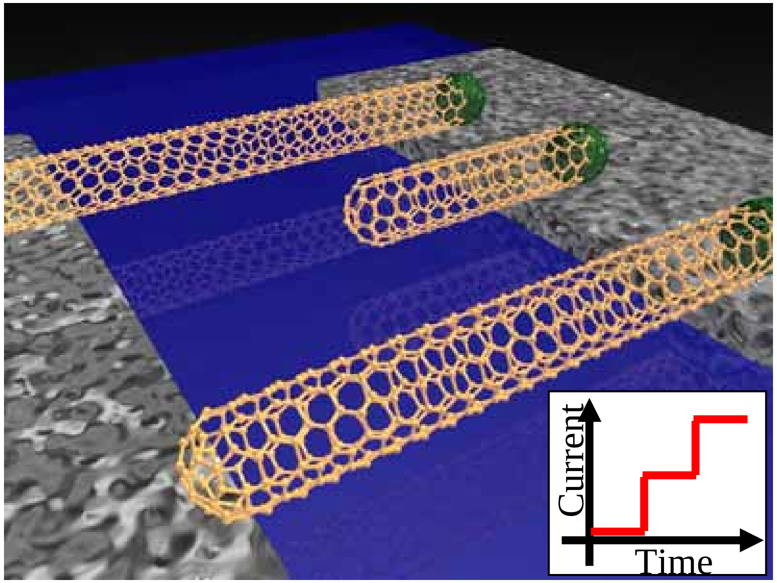
Electric field effect Growth
Source 10V Drain -10V Gate -40V

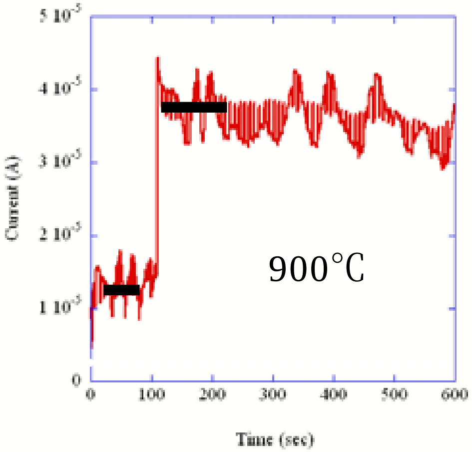
カーボンナノチューブの本数制御成長

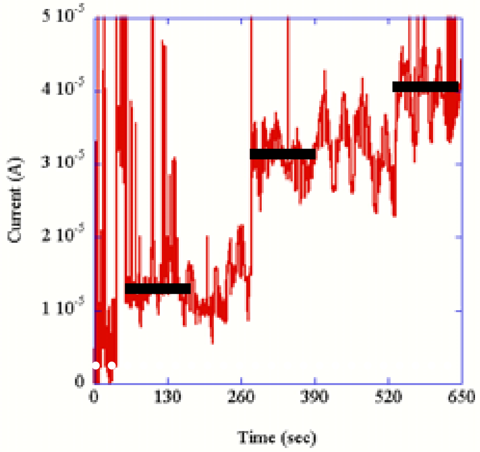




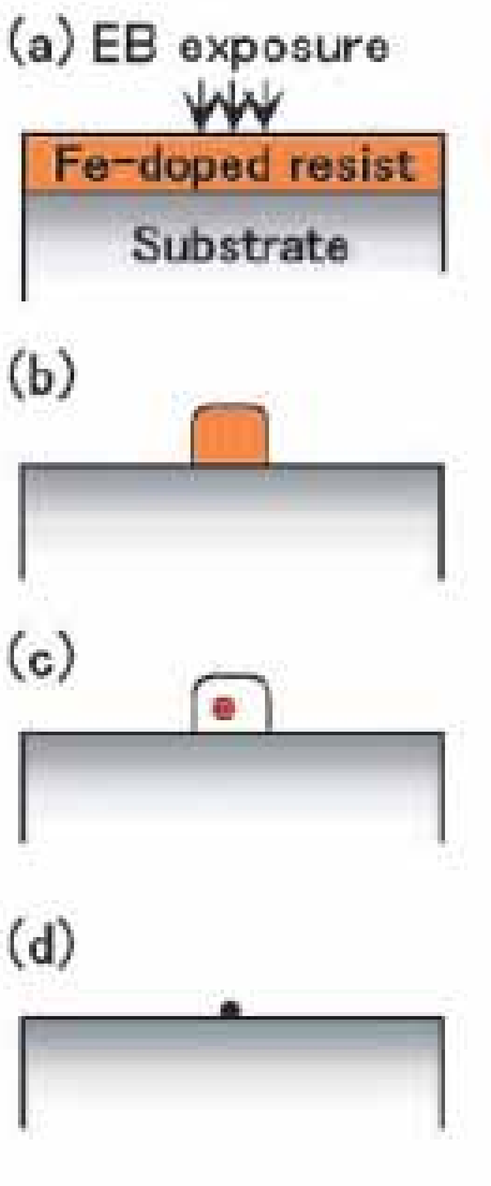




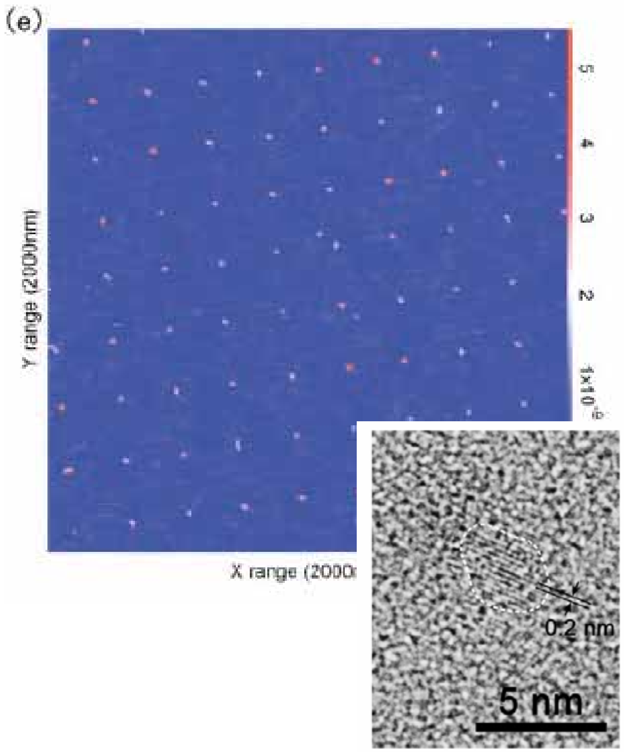




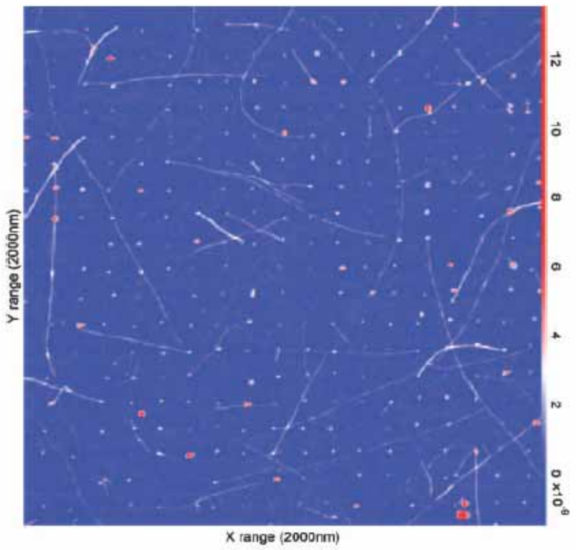
カーボンナノチューブの位置指定成長法



1) 直径1nm の鉄微粒子を任意の位置におく

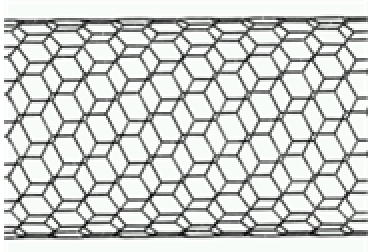


2) 鉄微粒子からカーボンナノチューブの成長



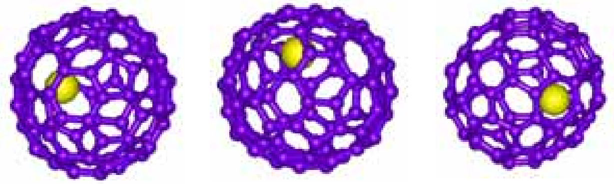
Peapod　ピーポッドの合成

開口した
SWNT



ドープ

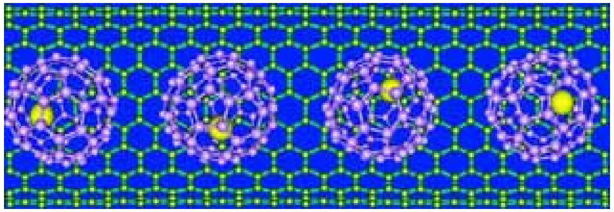
金属内包フラーレン $M@C_{XX}$



SWNTs

フラーレン

真空封管したガラスアンプルを450-500°Cで2日間

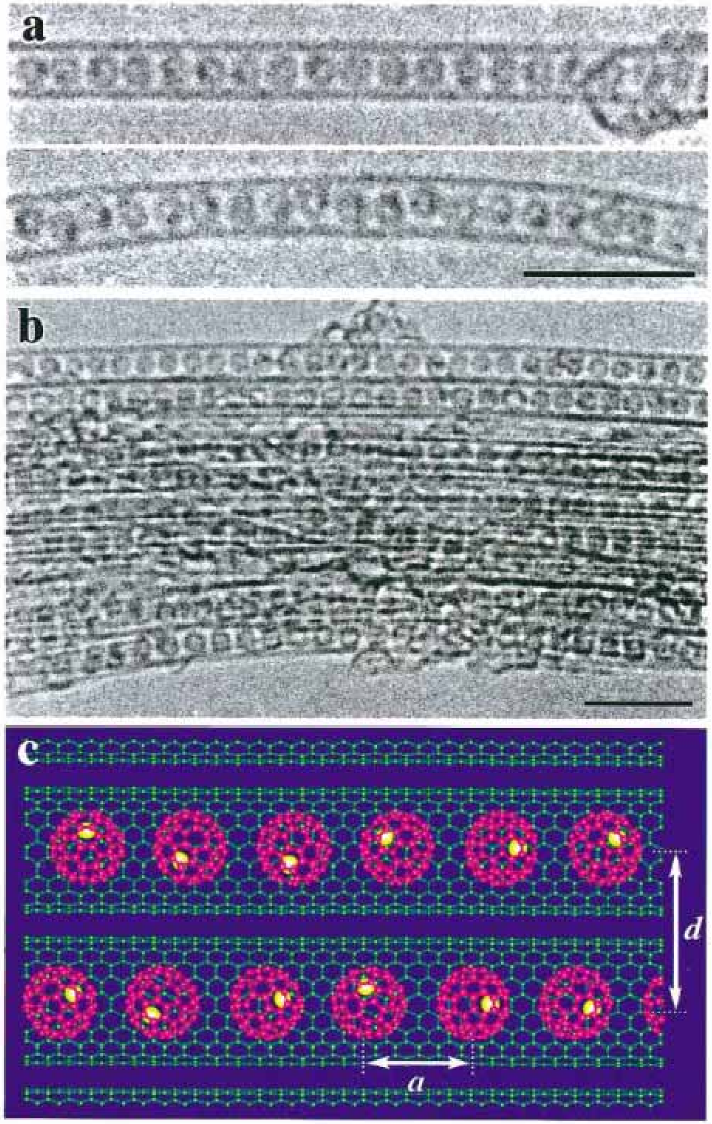


ピーポッド

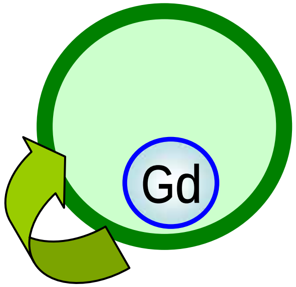
$(M@C_{XX})_n@SWNT$
or
$M@C_{XX}$-peapod

金属内包フラーレンピーポッドの合成

Gd@C_{82} peapod



Gdが+3価の状態であることを示す。EELS測定



$Gd^{3+}@C_{82}^{3-}$

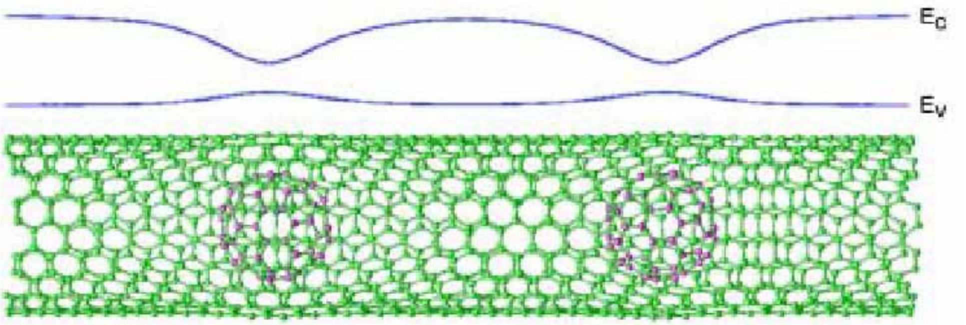
K.Hirahara *et al.*,
Phys.Rev.Lett. **85**, 5384 (2000).
K. Suenaga *et al.*,
Science **290**, 2280 (2000).
K.Hirahara *et al.*,
Phys.Rev.Lett. **85**, 5384 (2000).

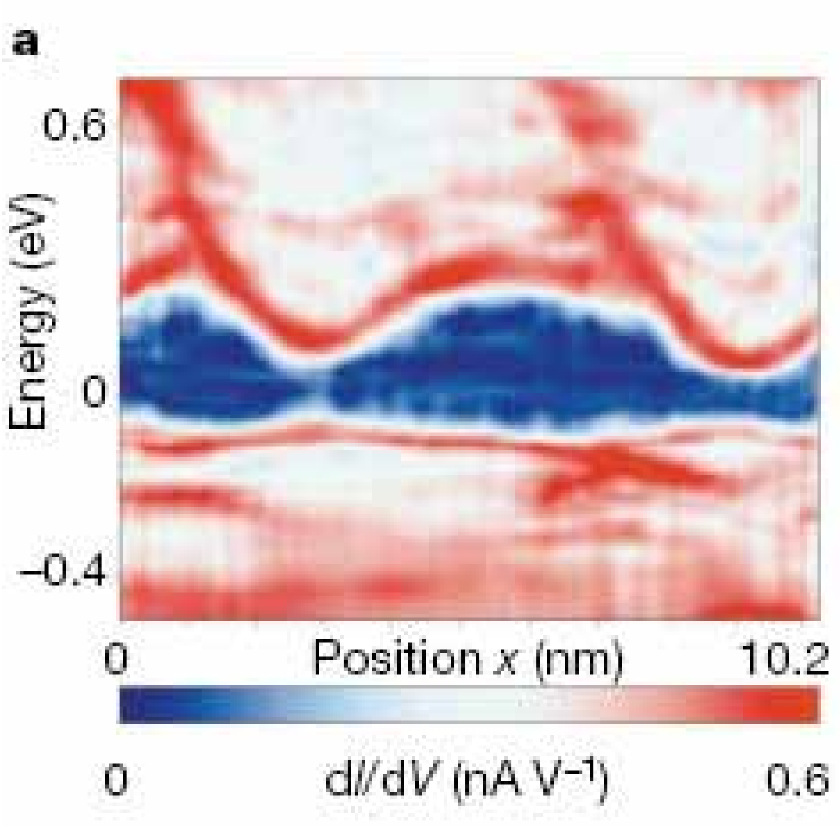
- **金属内包フラーレンピーポッド**

	電荷移動数
Gd@C_{82}	+3
Dy@C_{82}	+3
Ti_2@C_{80}	+4
Ce_2@C_{80}	+6
Gd_2@C_{92}	+6

STS - Gd@C$_{82}$ Peapod

J. Lee *et al*. Nature **415** 1005 (2002)





Gd@C$_{82}$付近で
伝導帯端が大きく変調

⇒　バンドギャップ変調

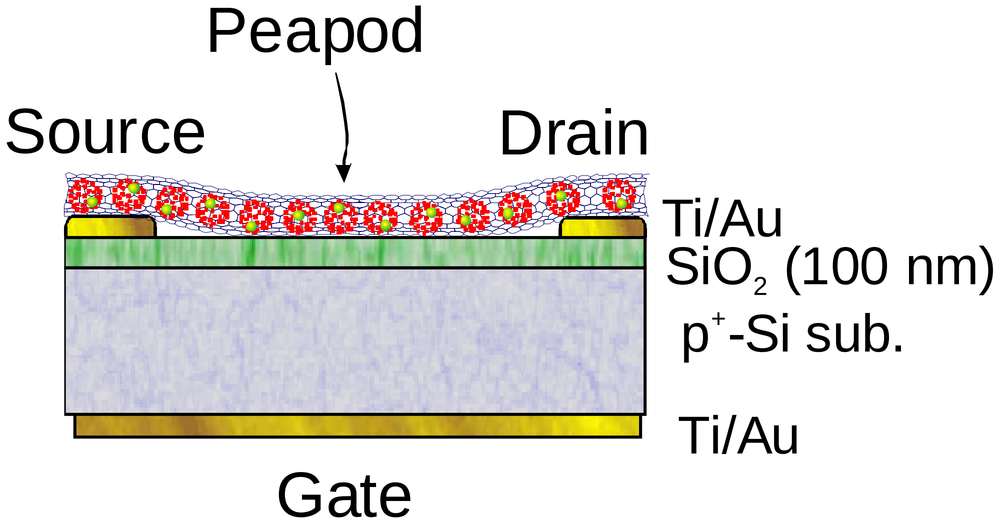
Peapod FET　ピーポッドFETの作製

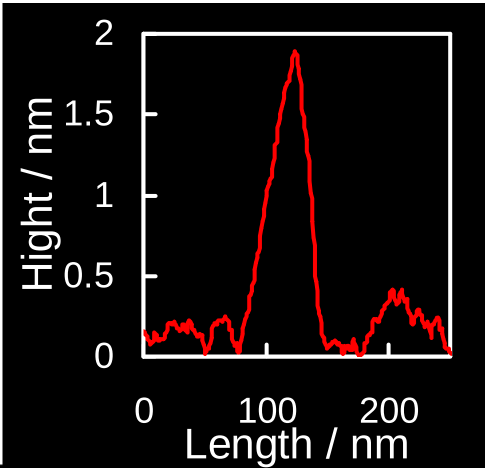
- **電子線露光による電極形成**
- **ピーポッドの分散液を滴下**

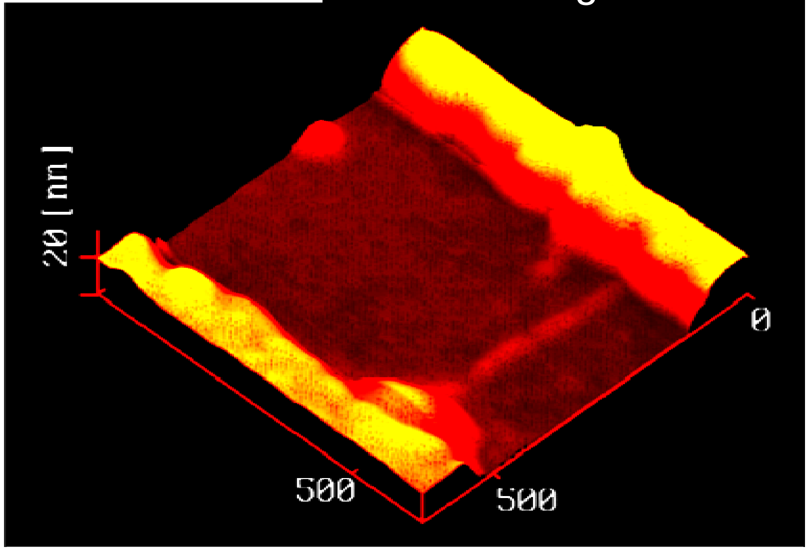
内包したフラーレン

- C_{60}, C_{78}, C_{90}
- **金属内包フラーレン**

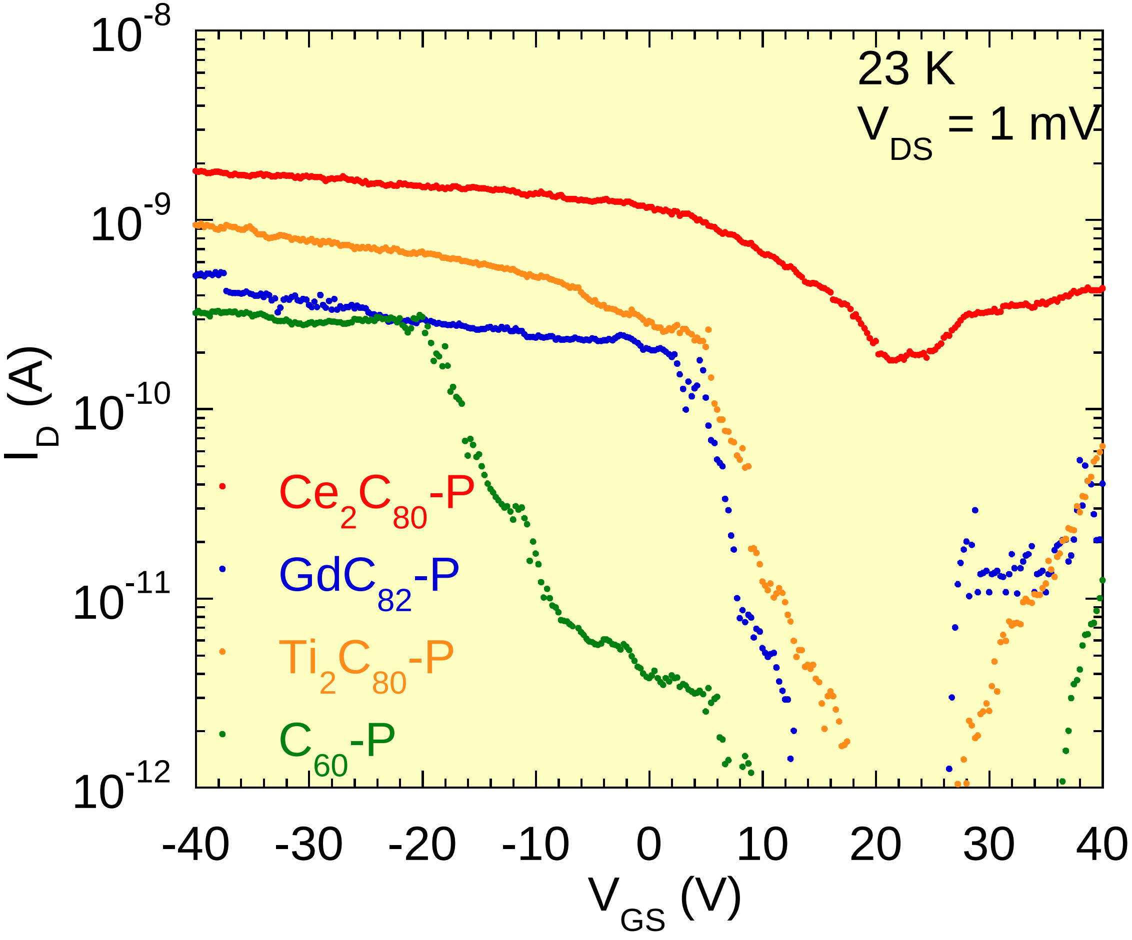
  ($Gd@C_{82}$, $Ti_2@C_{80}$, etc.)







Various Type Peapod FET and its I_D-V_{GS} Characteristics



- **金属内包フラーレンピーポッド**

	電荷移動数
$Ce_2@C_{80}$	+6
$Ti_2@C_{80}$	+4
$Gd@C_{82}$	+3
C_{60}	+0

1）通常のSWNT FET

- p**型**

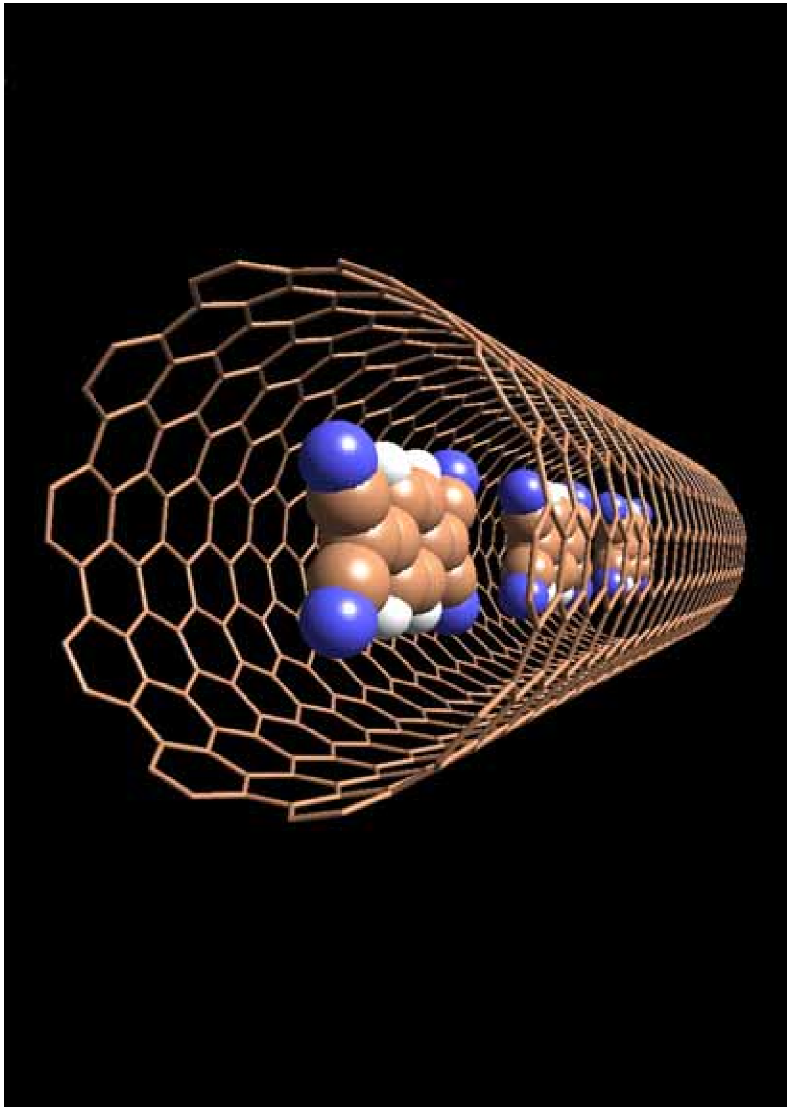
2）$Ti_2@C_{80}$**ピーポッド**FET

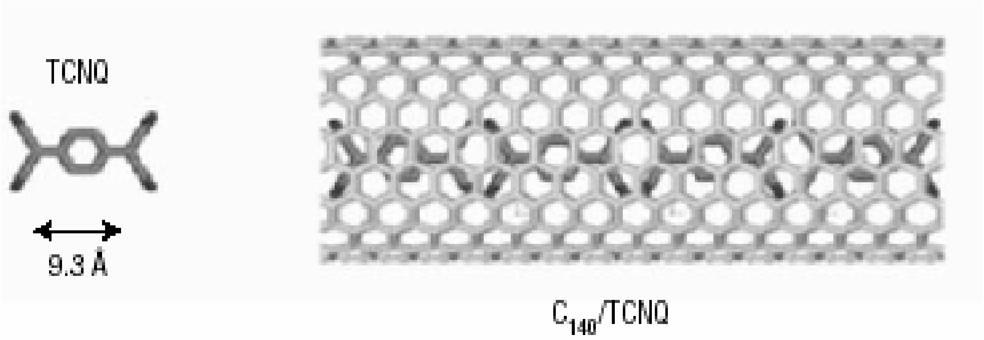
- p / n **両極性**

3）オフ領域の電圧幅

- **バンドギャップを反映**

Various Organic Molecular Doping into Carbon Nanotube





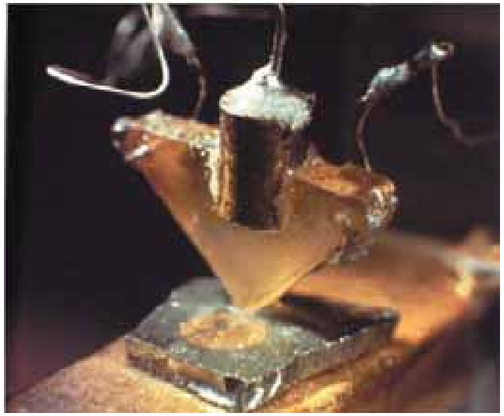
- 有機分子からCNTへ電子の移行
- CNTの伝導特性が制御可能？

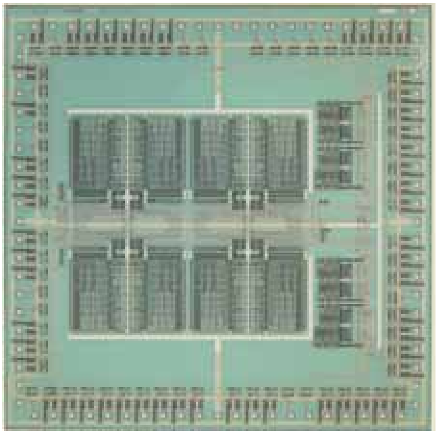
Structure was determined by Spring-8.

カーボンナノチューブトランジスタ

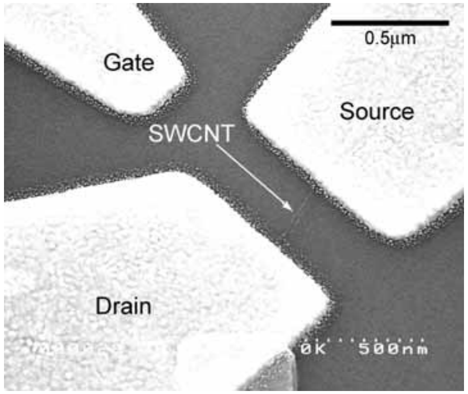
集積回路て何？
何を集積しているの？
材料は何？
サイズは？
現在の最高の集積度は？

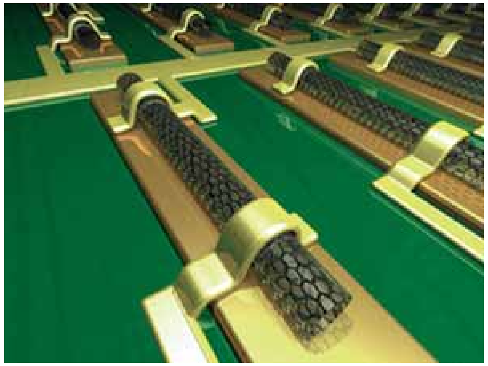
トランジスタ：５０年にわたる発展





カーボンナノチューブ ： 純粋科学から工学応用へ





MOSFET：Metal Oxide Silicon Field Effect Transistor
金属／酸化物／シリコン　電界効果トランジスタ

どこを小さくしているか

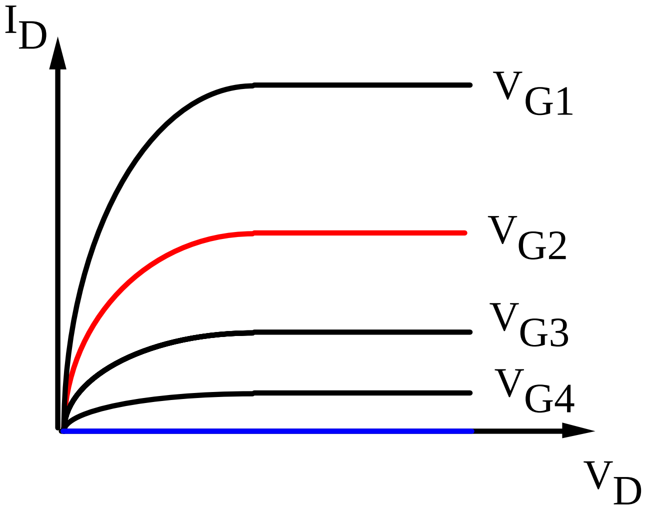
- ・ゲート長 : L
- ・絶縁膜厚さ : Ci
- ・移動度 : μ_v
- ・ゲート幅 : Z

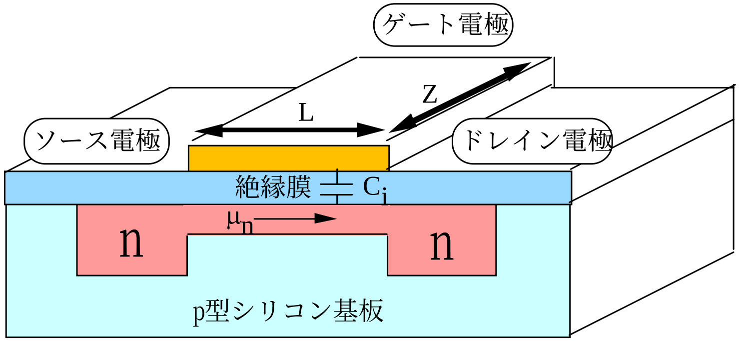
$$I_{Dsat} = \frac{Z}{2L}\mu_n C_i (V_G - V_T)^2$$

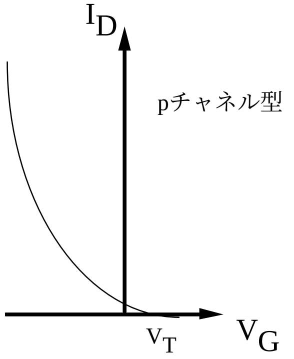
ドレイン電流

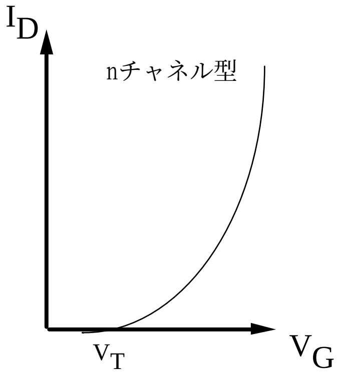
$$g_m = \frac{dI_{Dsat}}{dV_G} = \frac{Z}{L}\mu_n C_i (V_G - V_T)$$

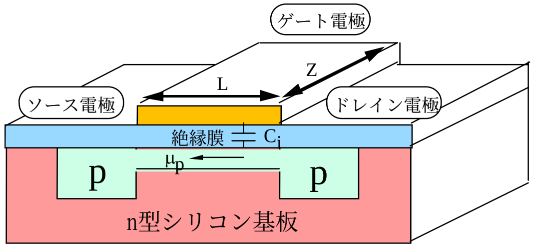
相互コンダクタンス（増幅率）



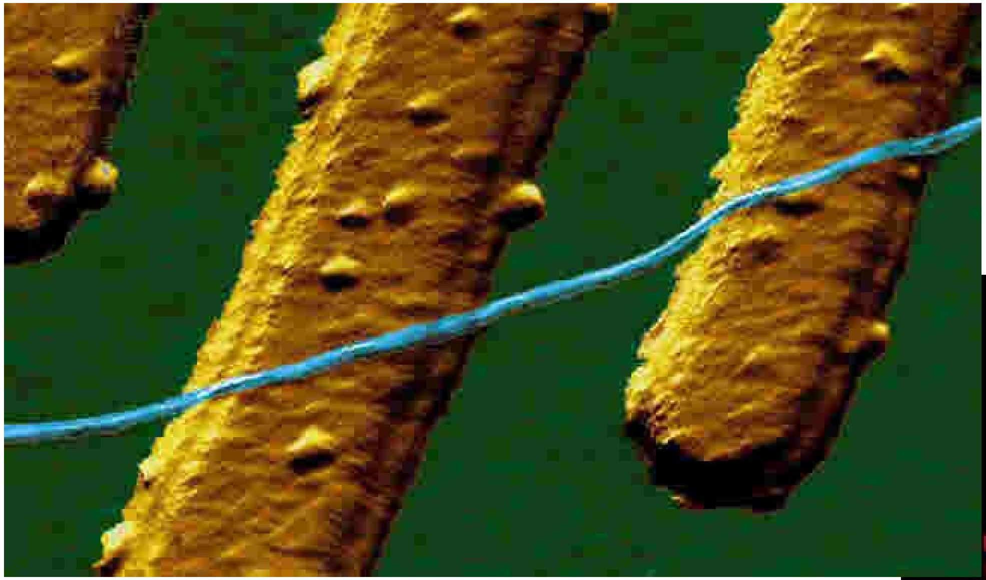




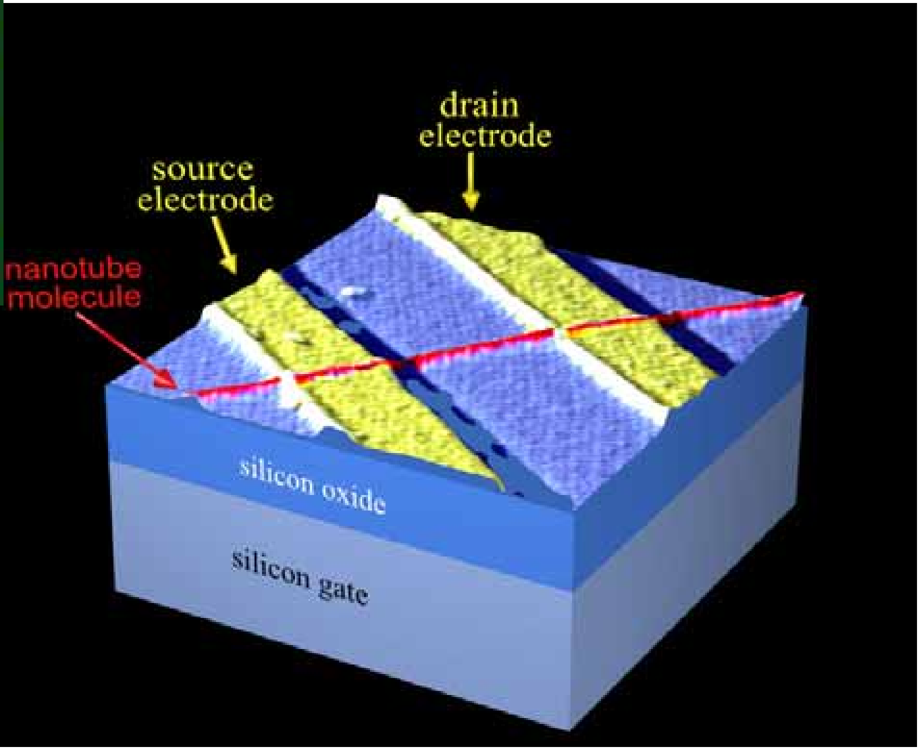


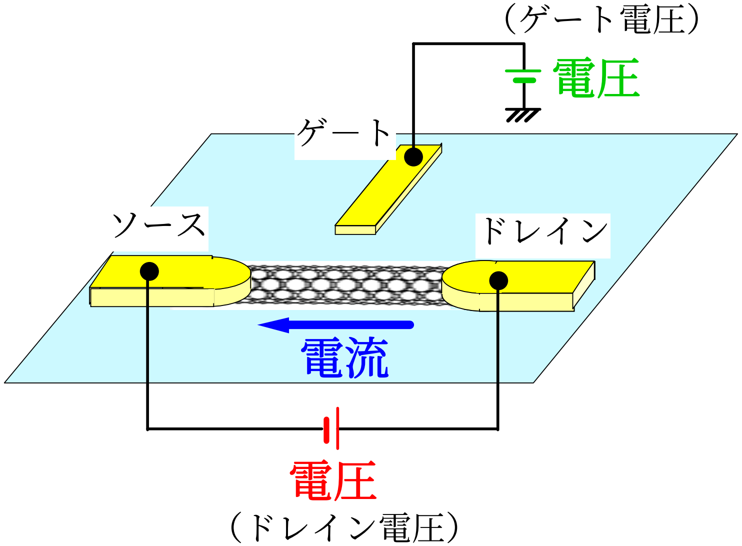


カーボンナノチューブの電気伝導特性を測定する



Delft University
オランダ

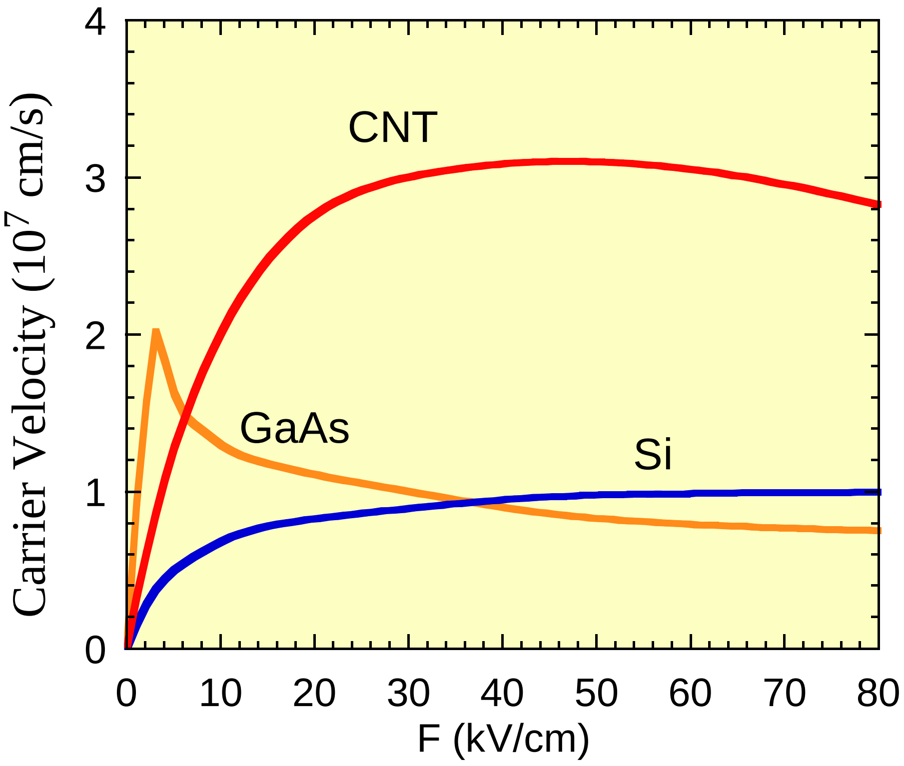




カーボンナノチューブのキャリアの移動度と速度の理論値

	Eg (eV)	**移動度** (cm^2/Vs)
CNT (25,0): 1.99 nm	0.45	**65,000**
(19,0): 1.51 nm	0.60	**35,500**
(13,0): 1.03 nm	0.87	15,000
Si	1.12	e: 1,500 h: 450
GaAs	1.42	e: 8,500 h: 400
InAs	0.36	e: 33,000 h: 460

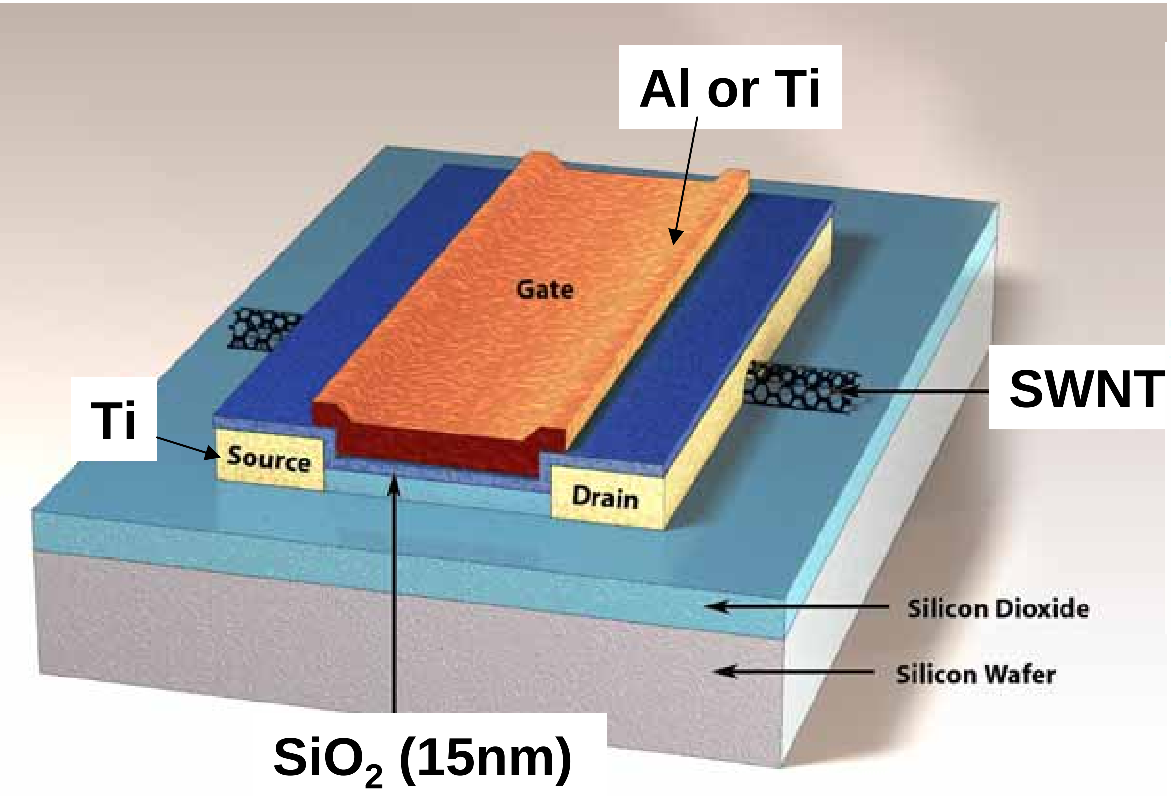
V. Perebeinos et al. (IBM) PRL 94, 086802 (2005)
S. M. Sze, Physics of Semiconductor Devices 2nd Ed.



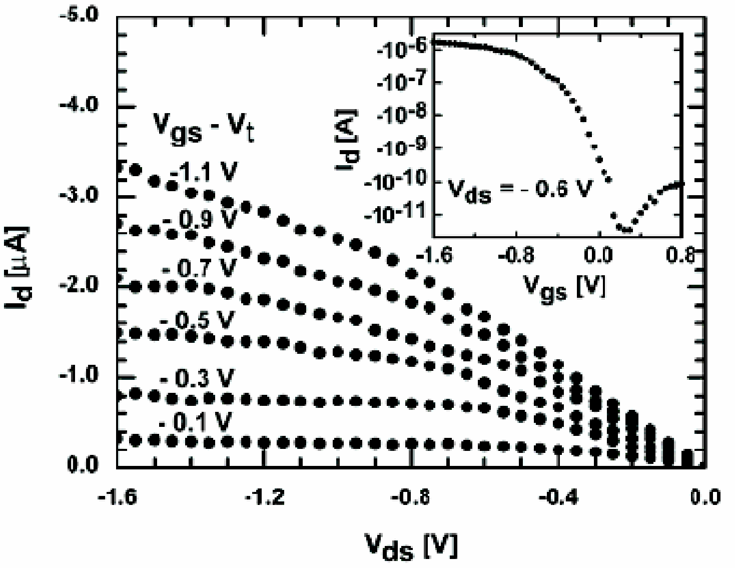
(G. Pennington et al. SISPAD’02, 279 (2002))

名大：大野雄高氏 提供図面

IBMのﾄｯﾌﾟｹﾞｰﾄ型CNTﾁｬﾈﾙFET p type

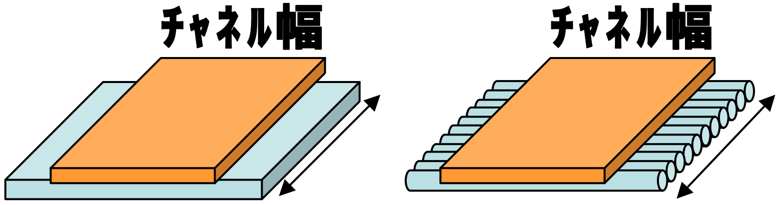


S. J. Wind, et al., APL 80 (20), 3817 (2002)



相互ｺﾝﾀﾞｸﾀﾝｽ g_mが
Si-MOSFETの2倍以上

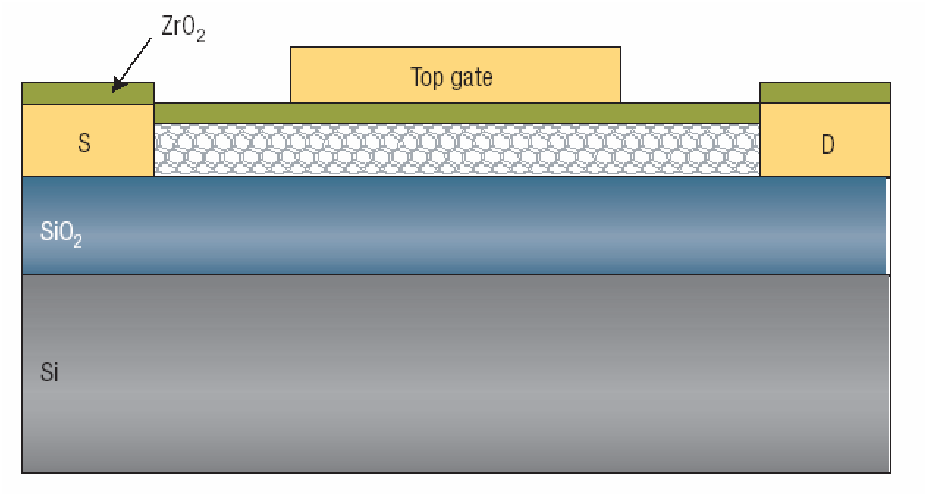
	CNT-FET	Si-pMOS
Lg （nm）	260	15
t_{ox} （nm）	15	1.4
V_{th} (V)	-0.5	-0.1
I_{on} （mA/mm）	2100	265
g_m (μS/μm)	2321	975



もし同じﾁｬﾈﾙ幅が実現できれば

High-k ｹﾞｰﾄ絶縁膜を用いたCNT-FET

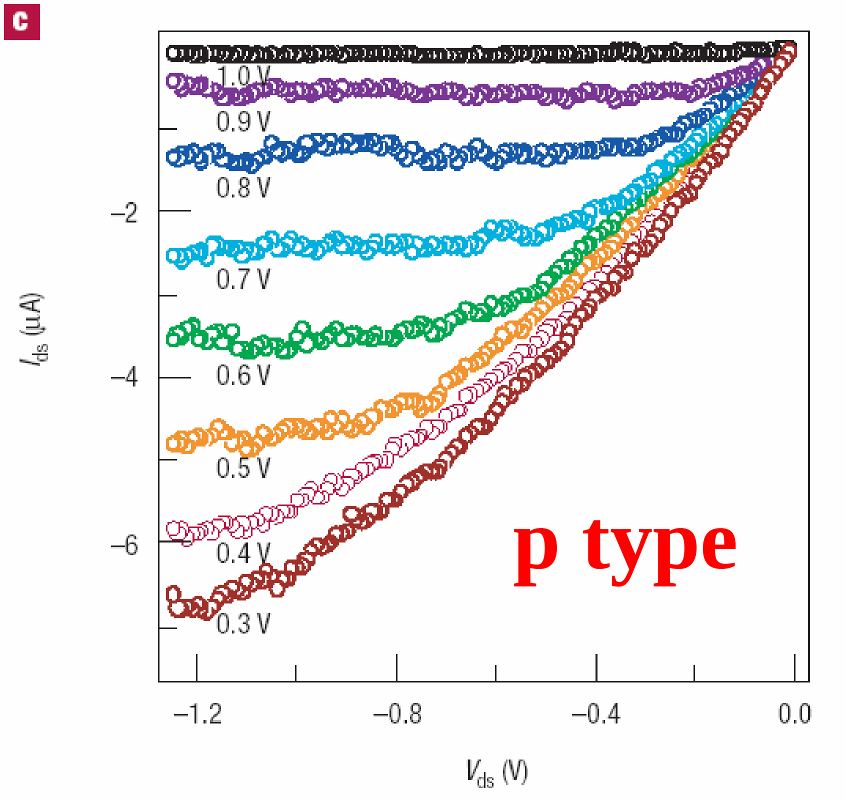
Stanford Univv. ：A. Javey et al. Nature Mat. 1, 241, 2002.



ZrO$_2$ (k ~ 25) : 8 nm

（SiO$_2$ (k ~ 3): 0.9 nmに相当）

⇒ C_Gの増大



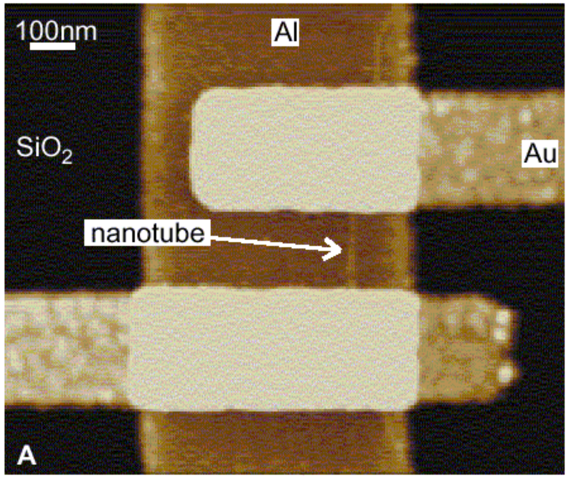
p type

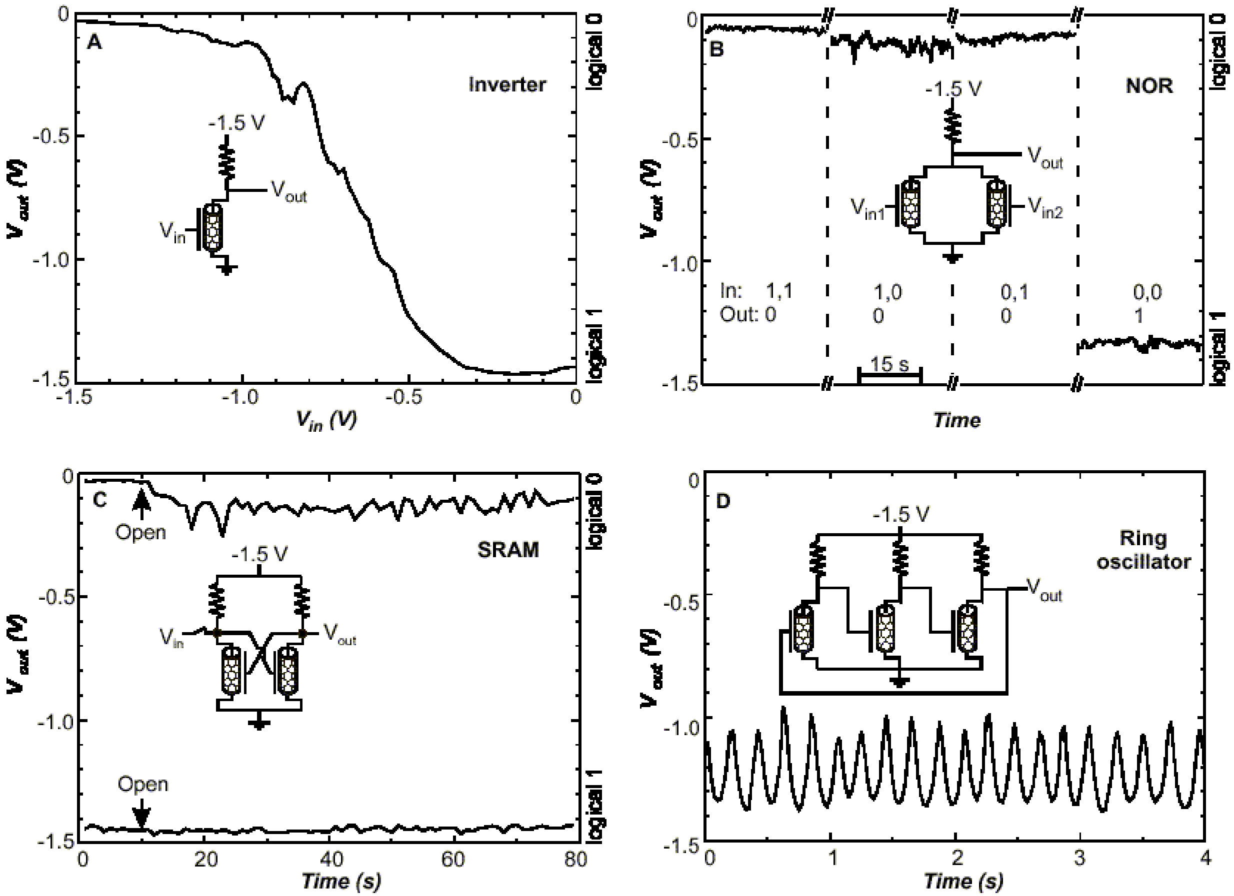
I_{ON}/I_{OFF} ~ 10^4, g_m = 6000 μS/μm, s-factor = 70 mV

名大）大野、水谷氏提供

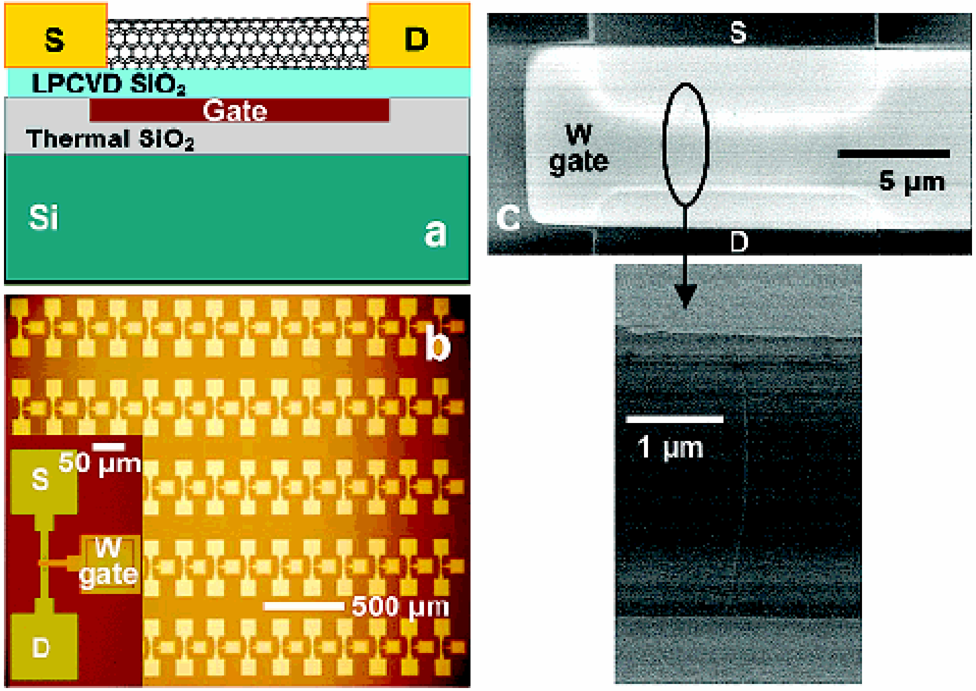
n type Carbon Nanotube FET Logic

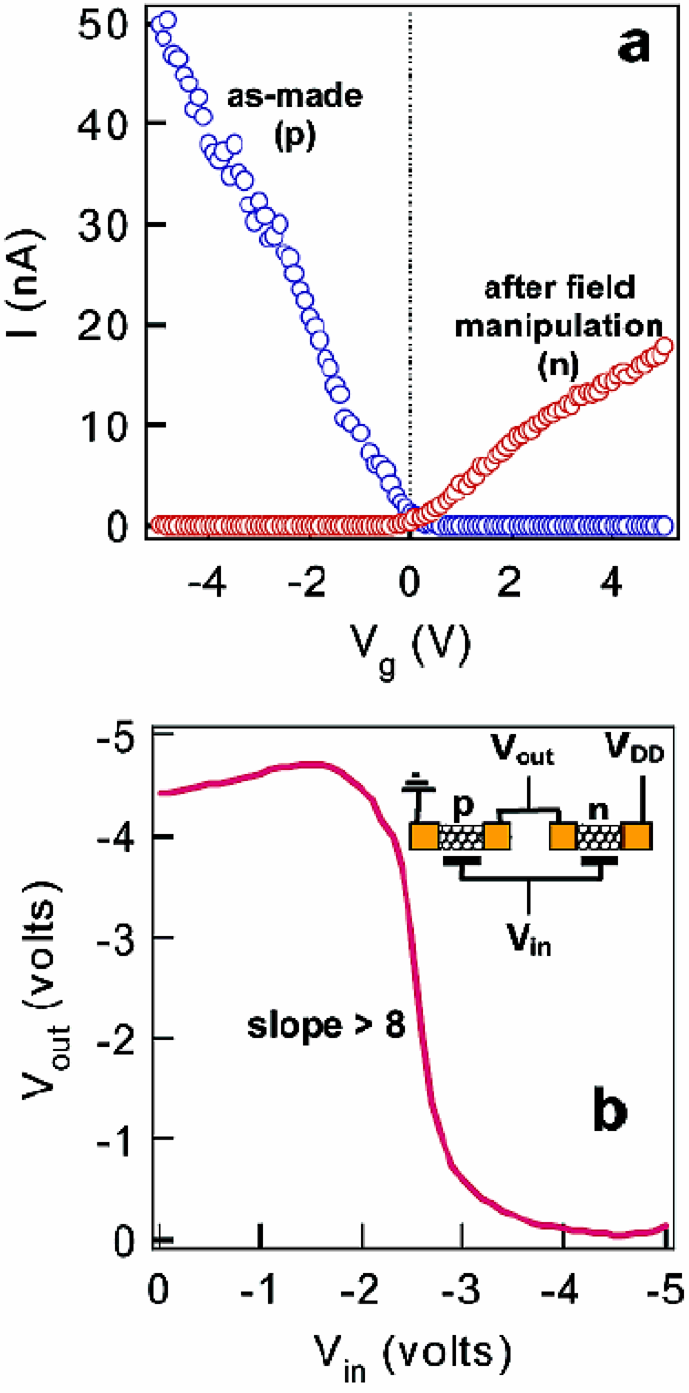
n型カーボンナノチューブFET回路

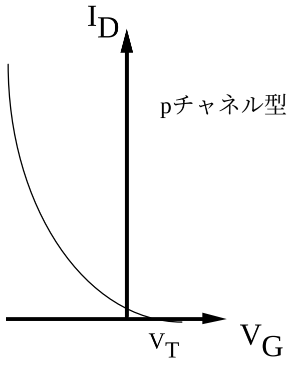


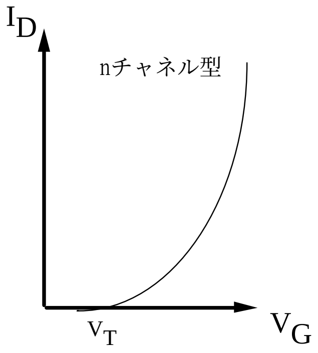


相補型回路


S
D
LPCVD SiO₂
Gate
Thermal SiO₂
Si
a
b
50 µm
S
W gate
D
500 µm
S
W gate
5 µm
C
D
1 µm

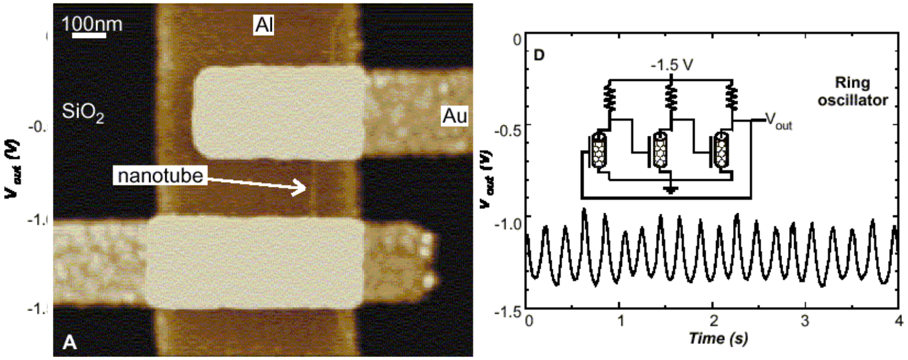

a
as-made (p)
after field manipulation (n)
I (nA)
50
40
30
20
10
0
-4
-2
0
2
4
V_g (V)
b
V_out
V_DD
p
n
V_in
slope > 8
V_out (volts)
-5
-4
-3
-2
-1
0
0
-1
-2
-3
-4
-5
V_in (volts)


I_D
pチャネル型
V_T
V_G

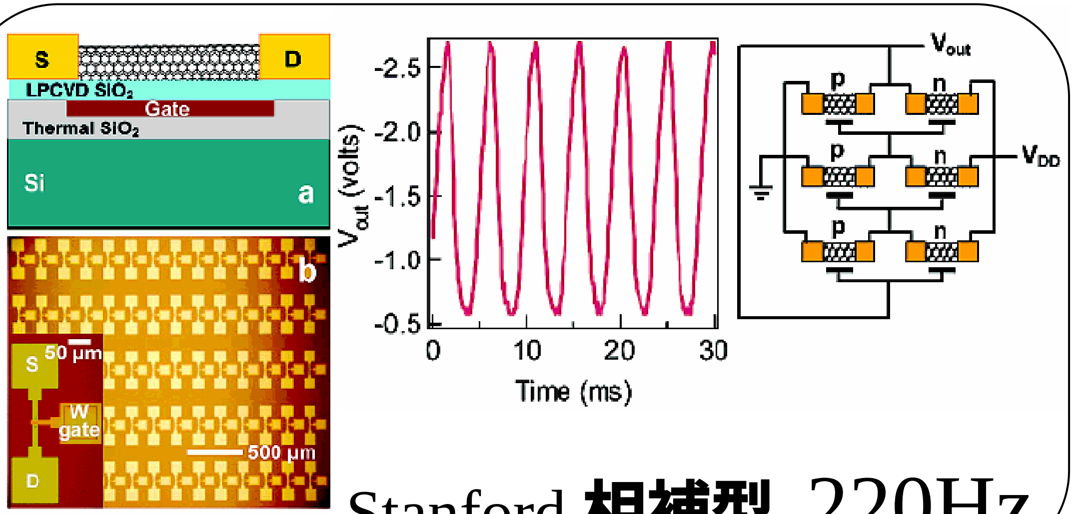

I_D
nチャネル型
V_T
V_G

−5 V.

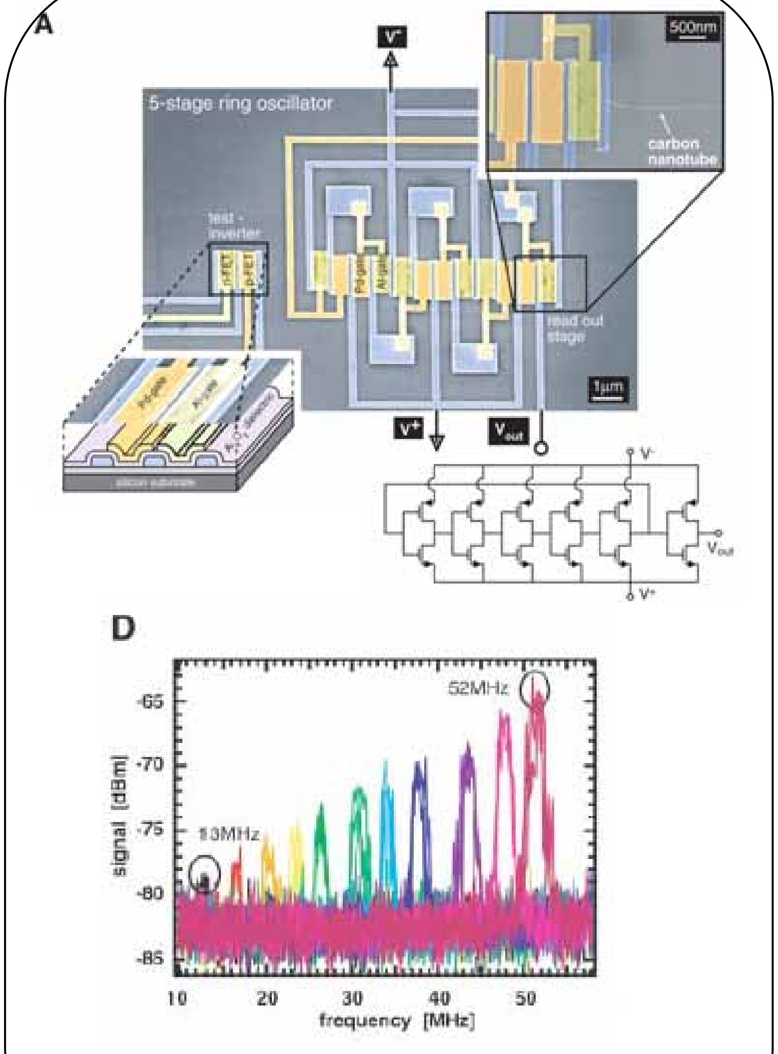
カーボンナノチューブ FET リング発振器



Delft p**型** 5 Hz

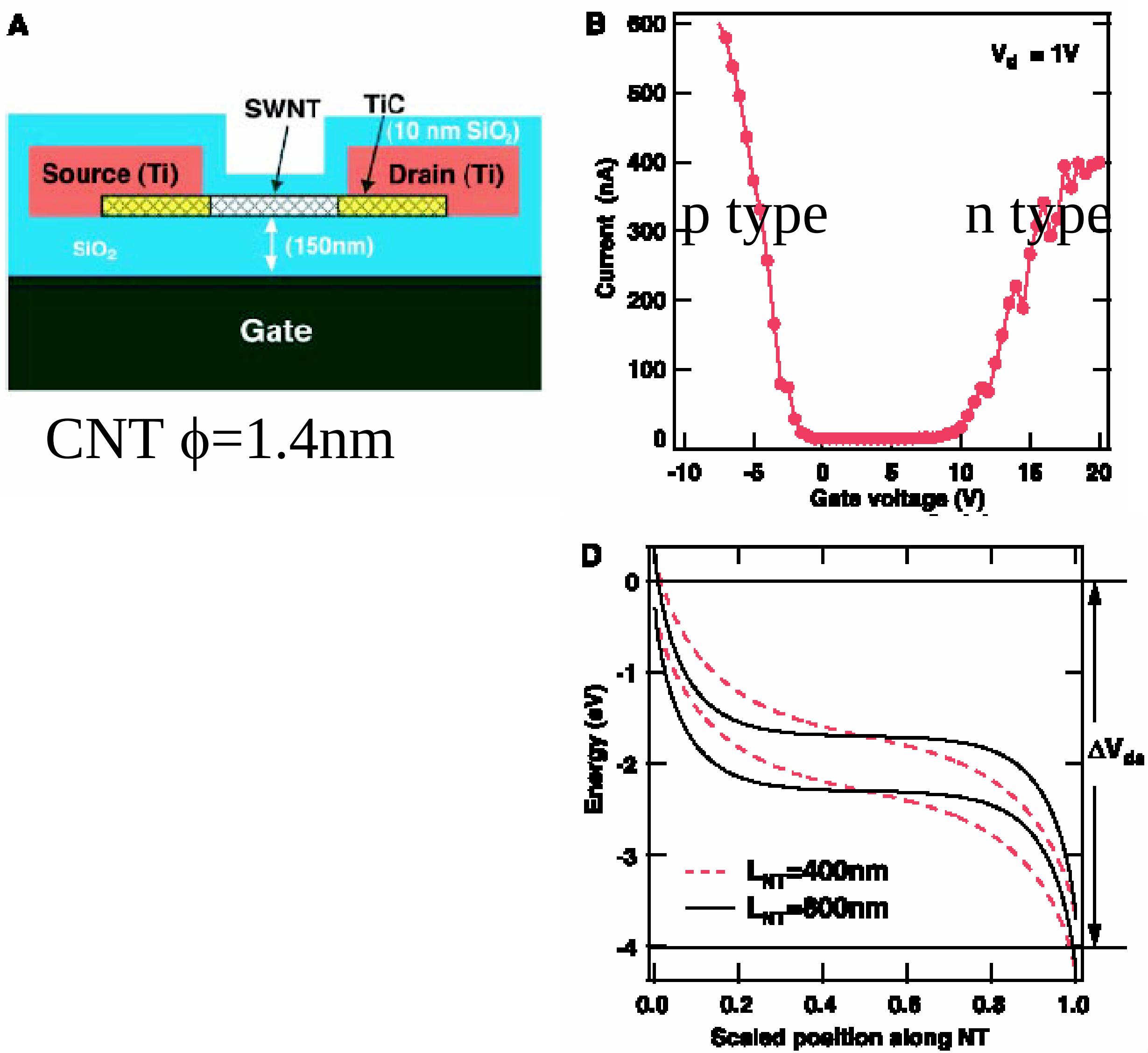


Stanford **相補型** 220Hz



IBM **相補型** 52MHz

カーボンナノチューブの発光　IBM



p type

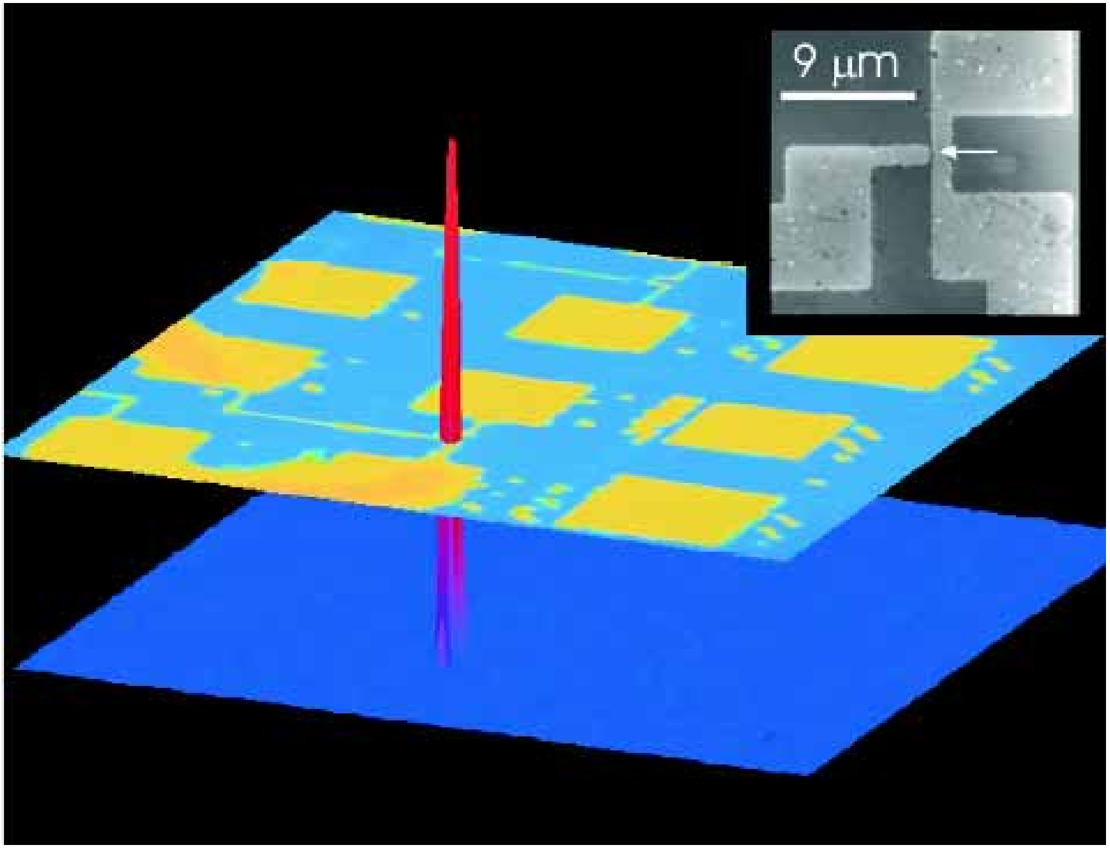
n type

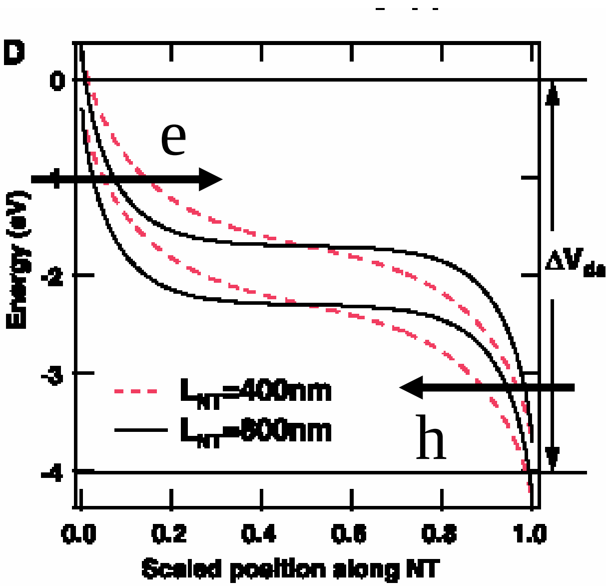
CNT ϕ=1.4nm

atic diagram of the ambipolar s-SWNT device structure. (B) Electrical characterization of a typical ambipolar device. A plot of the drain current versus V_g for a grounded source and a small drain potential of 1 V is shown. The data indicate ambipolar behavior. (C) Plot of the drain current versus V_d for a grounded source and a gate potential of 5 V for the device used in the optical measurements. The inset shows the data on a logarithmic scale. (D) Calculated band structure for carbon nanotube FET devices with V_d = 4 V and V_g halfway between the source and drain voltages. The bands were calculated using channels 800 nm (black) and 400 nm (red) long and a 150-nm silicon dioxide gate insulator layer.

カーボンナノチューブの発光

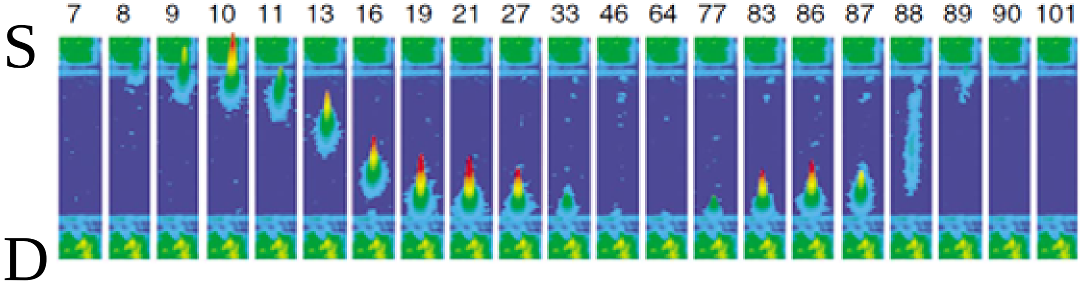
IBM





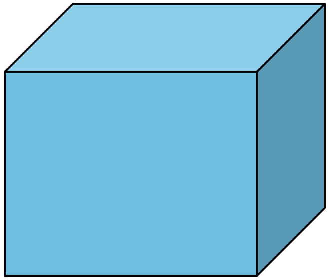
Drain Bias 0 → 10V(3 sec.) Repeat
190 sec. Integration

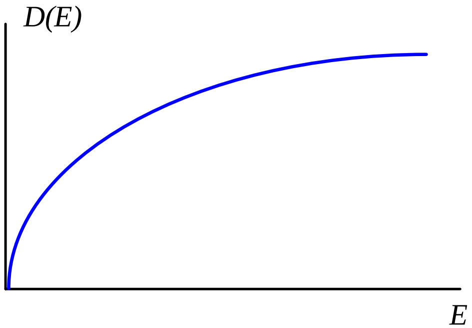
Fig. 2. Optical emission from an ambipolar carbon nanotube FET detected with an IR camera. The upper plane is a color-coded IR image of the carbon nanotube FET. The contact pads and thin wires leading to the carbon nanotube channel are shown in yellow. The lower plane is the surface plot of the IR emission image taken under conditions of simultaneous e⁻ and h⁺ injection into the carbon nanotube. The emission was localized at the position of the carbon nanotube. (Inset) SEM showing the device structure in the region of the nanotube emitter.



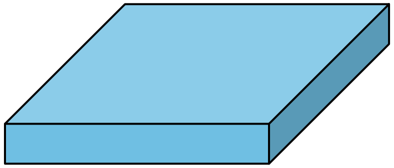
状態密度 D(E)

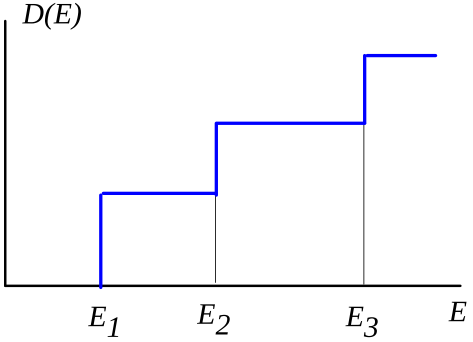
3次元

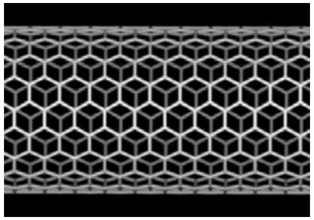




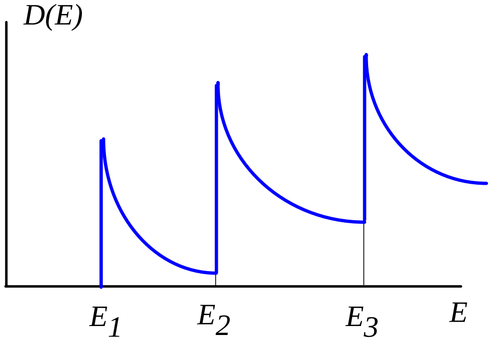
2次元



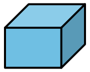


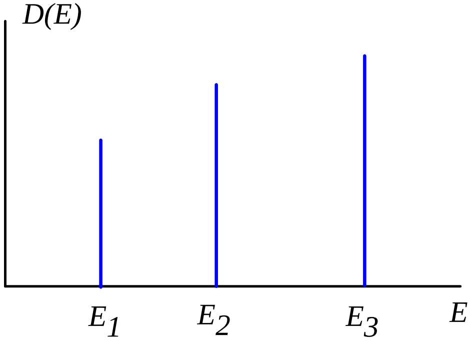


1次元



0次元



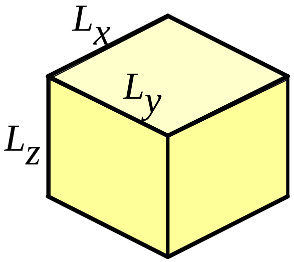


状態密度の算出　1次元量子細線の場合

３次元

$$D(E)=2\times\frac{dn_x \bullet dn_y \bullet dn_z}{dE}\times\frac{1}{L_xL_yL_z}$$

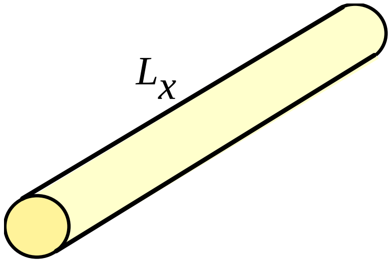
$$E=\frac{h^2}{8\pi^2 m}k^2=\frac{h^2}{8\pi^2 m}(k_x^2+k_y^2+k_z^2)$$



１次元

$$D(E)=2\times\frac{dn_x}{dE}\times\frac{1}{L_x} \qquad (1)$$

$$E=\frac{h^2k_x^2}{8\pi^2 m}=\frac{h^2}{8\pi^2 m}\left(\frac{n_x\pi}{L_x}\right)^2=\frac{n_x^2h^2}{8mL_x^2}$$



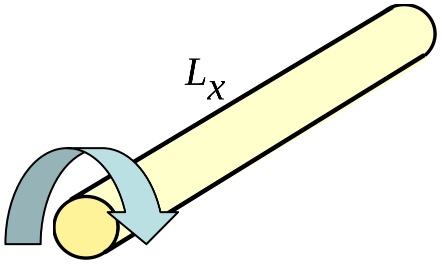
$$k_x=\frac{n_x\pi}{L_x}$$

$$n_x=\frac{2L_x\sqrt{2mE}}{h}$$

$$\frac{dn_x}{dE}=\frac{L_x}{h}\sqrt{\frac{2m}{E}} \qquad (2)$$

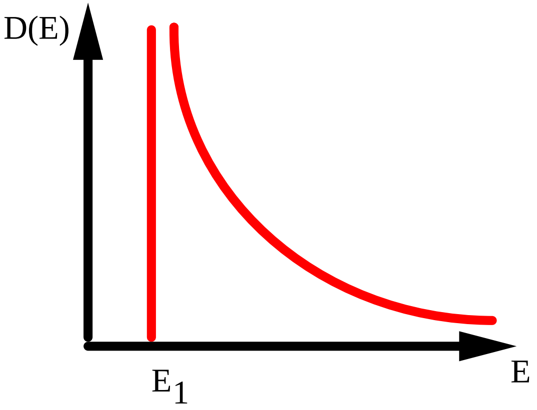
(1)(2)**式より**　$\therefore D(E)=\frac{4}{h}\left(\frac{m}{2E}\right)^{\frac{1}{2}}$

１次元状態密度

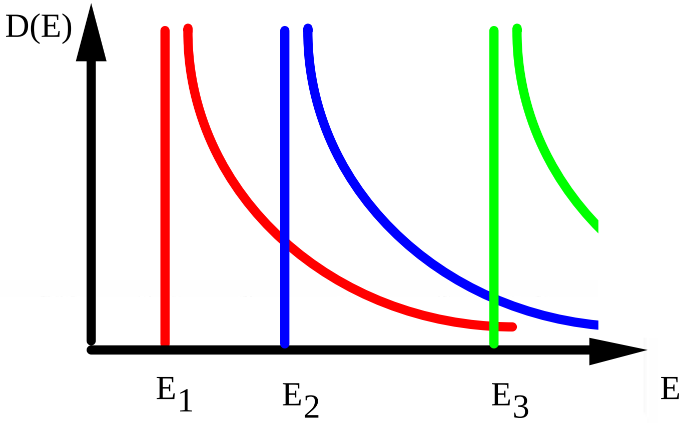


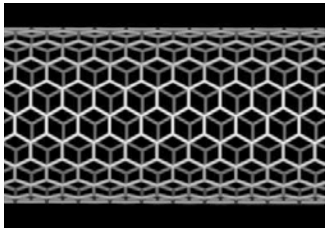
E_1, E_2 ･･･

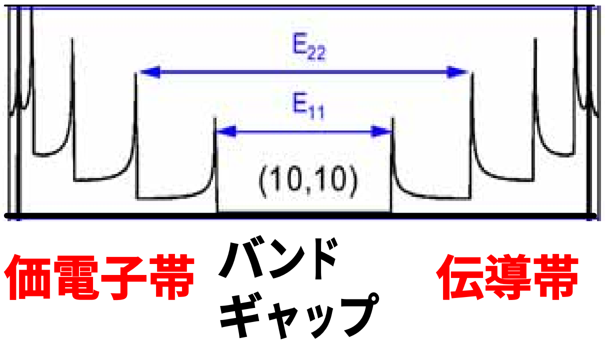
$$D(E) = \frac{4}{h}\left(\frac{m}{2E}\right)^{\frac{1}{2}}$$



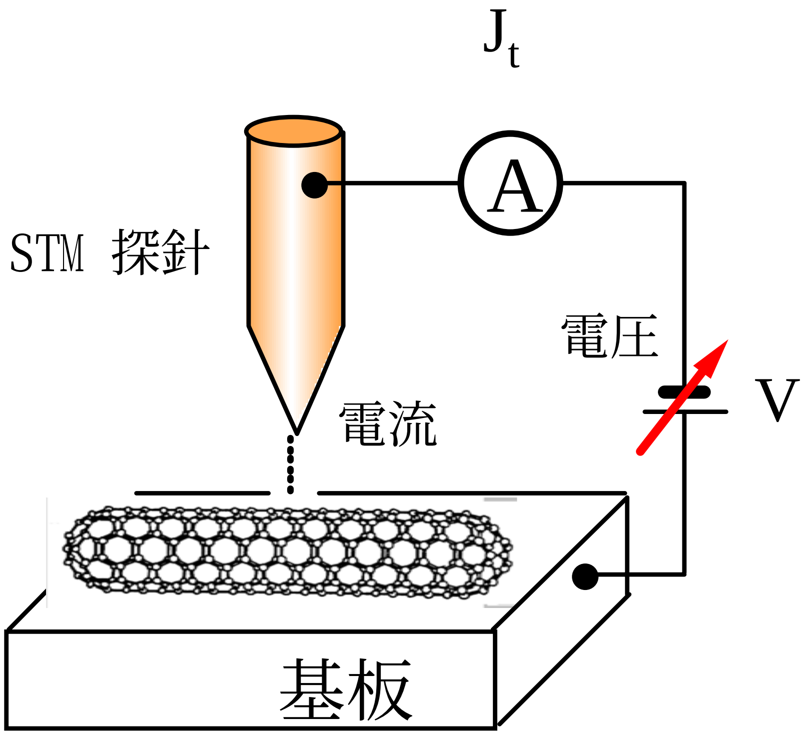
$$D(E) = \frac{g_s}{h}\left(\frac{m}{2(E - E_n)}\right)^{\frac{1}{2}}$$

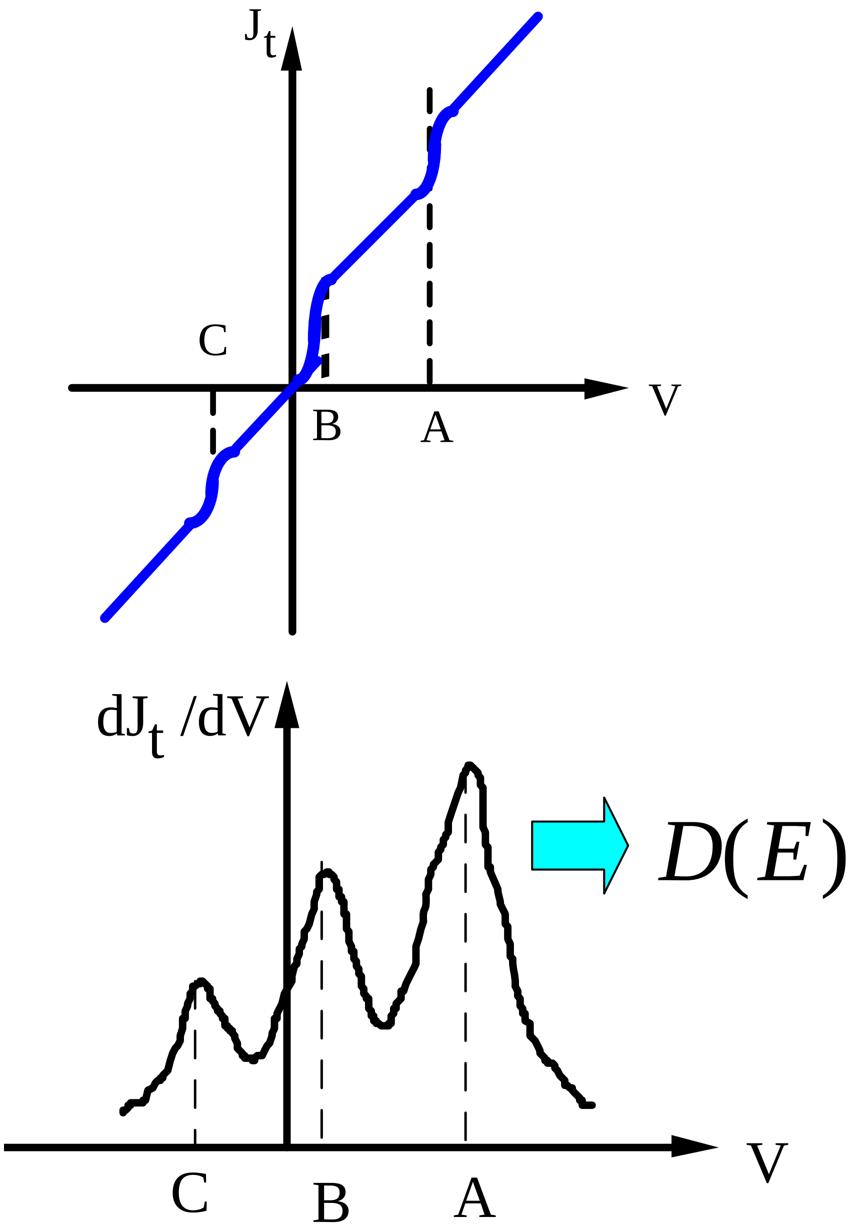




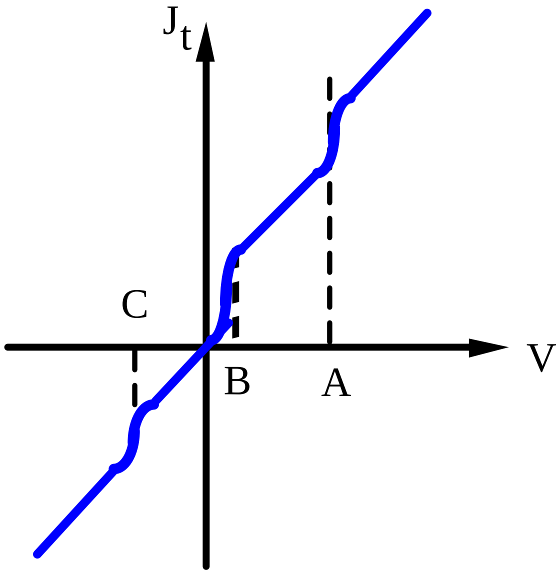


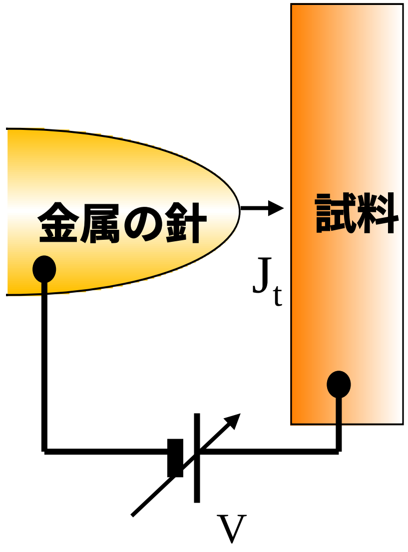
Scanning Tunneling Spectroscopy (STS)による電子状態密度の観測

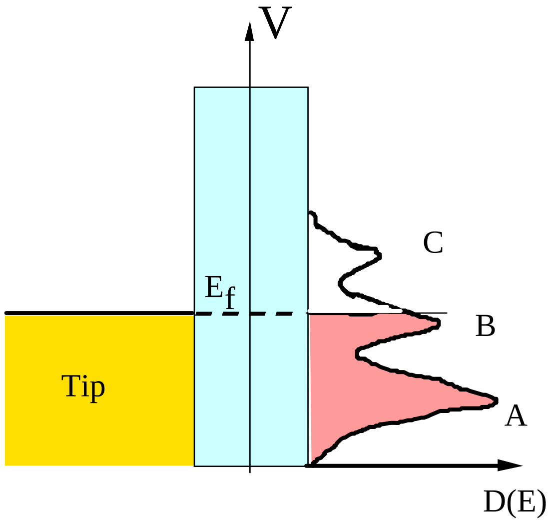


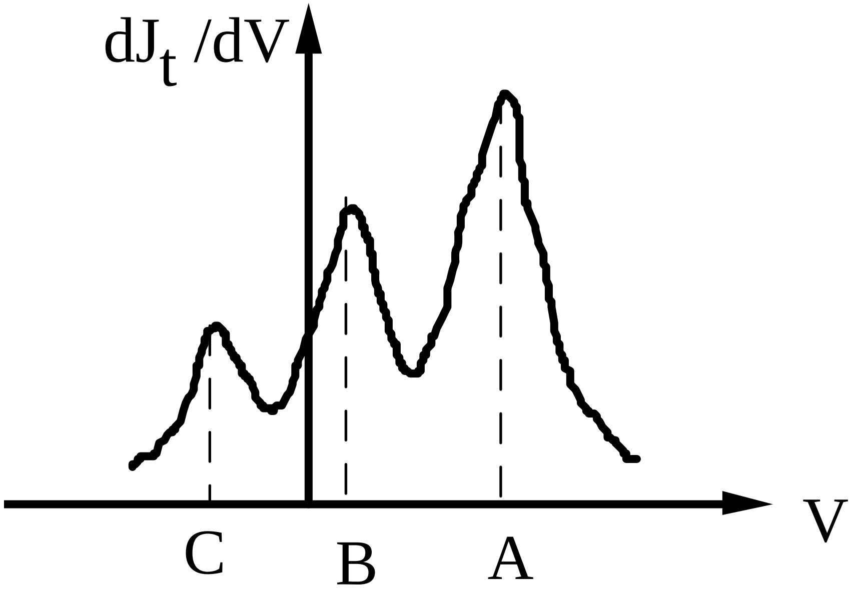


Scanning Tunneling Spectroscopy(STS) の原理









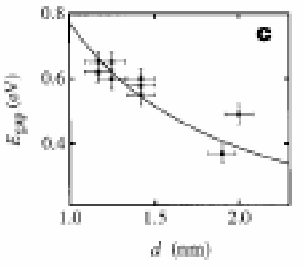
$$J_t \approx \int_0^{E_f} D(E)\bullet T(E,V)dE$$

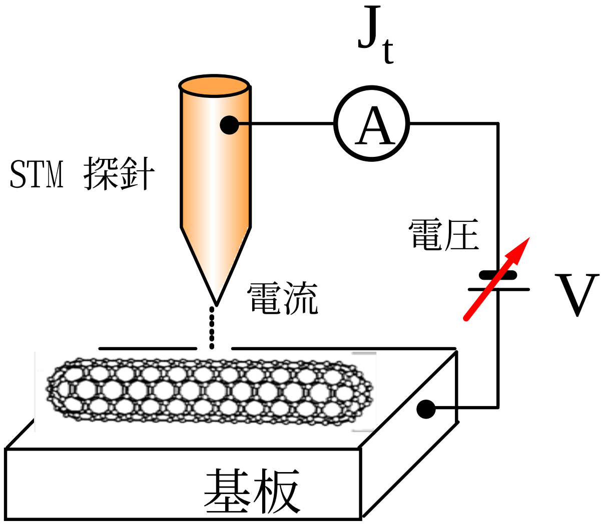
D(E) : **状態密度**

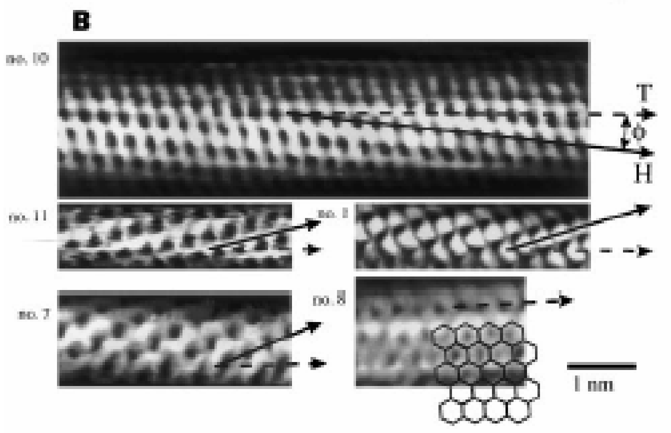
T(E,V):**トンネル確率**

$$\frac{dJ_t}{dV} \approx D(E)\bullet T(E,V) \approx D(E)$$

カーボンナノチューブのSTSの実験結果







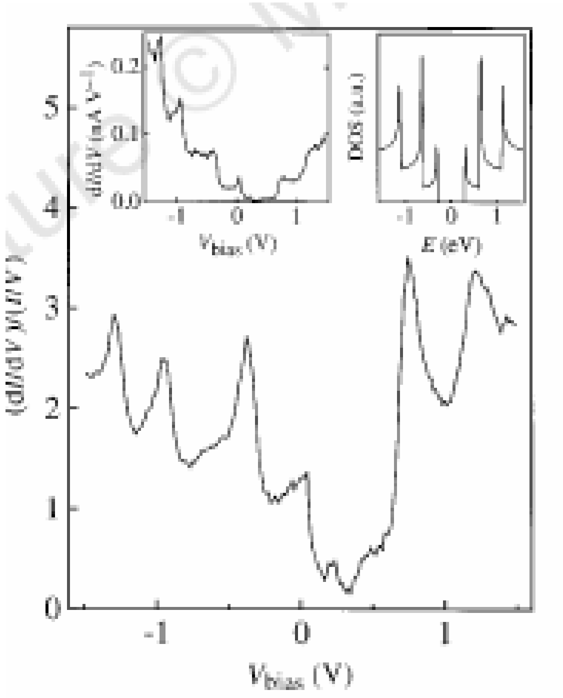
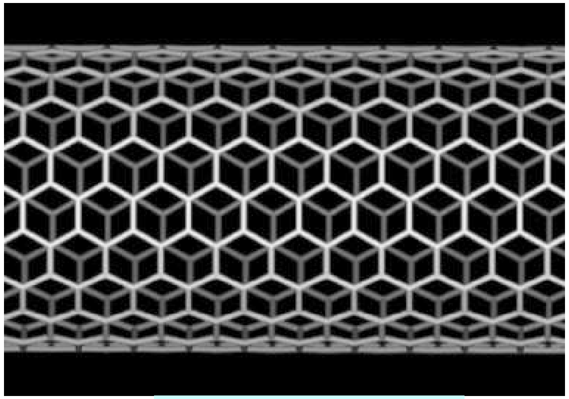
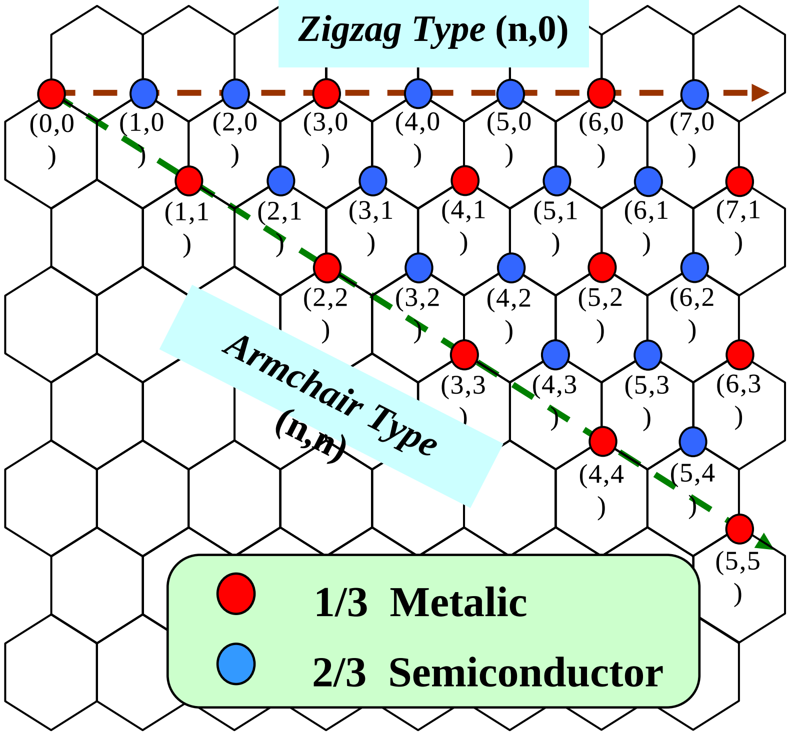


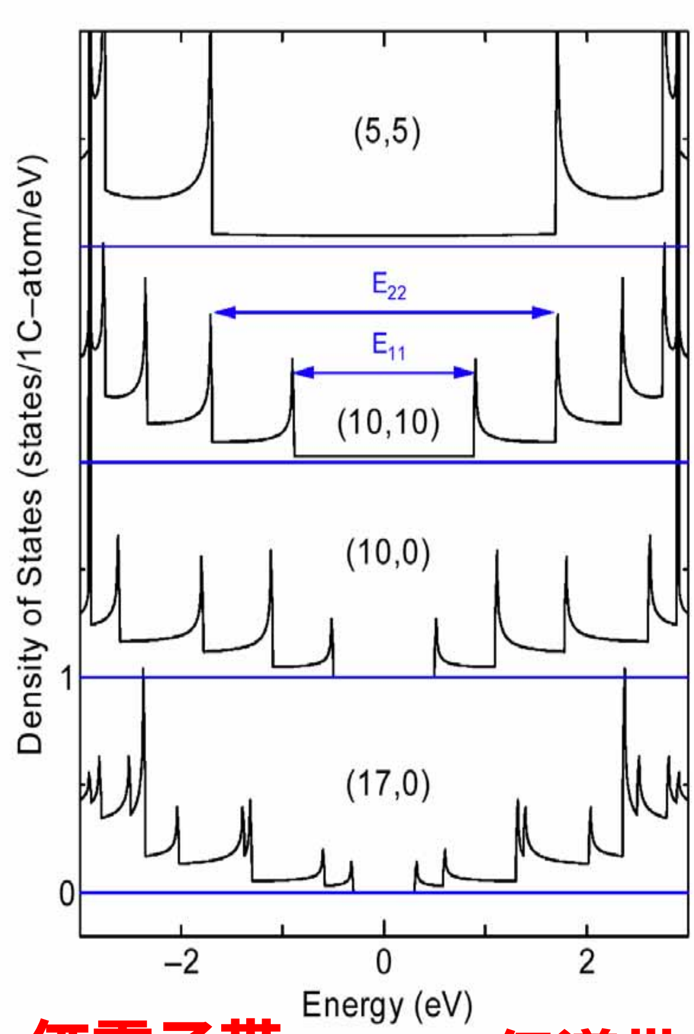
Figure 3 $(dI/dV)/(I/V)$ which is a measure of the density of states versus V for nanotube no. 9. The asymmetric peaks correspond to Van Hove singularities at the onsets of one-dimensional energy bands of the carbon nanotube. The left inset displays the raw dI/dV data. The right inset is the calculated density of states (DOS) for a (16,0) tube, which displays a typical example of the peak-like DOS for a semiconducting tube (a.u., arbitrary units). The experimental peaks have a finite height and are broadened, which we attribute to hybridization between the wavefunctions of the tube and the gold substrate. The overall shape of the experimental peaks however still resembles that predicted by theory.

単層カーボンナノチューブの状態密度

一次元量子細線





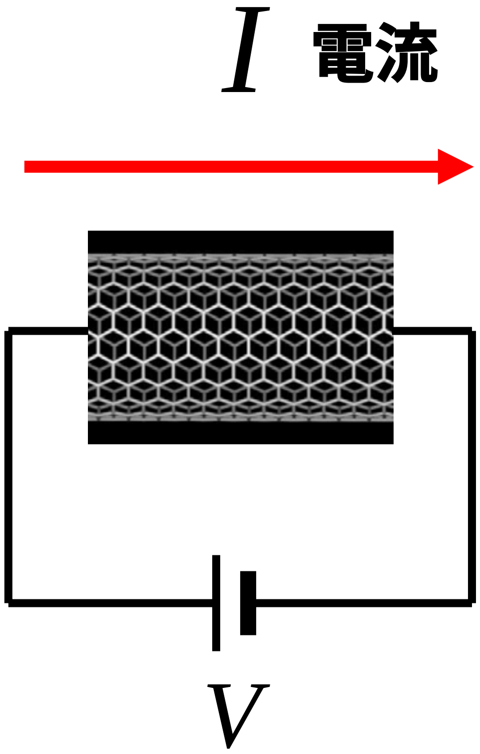


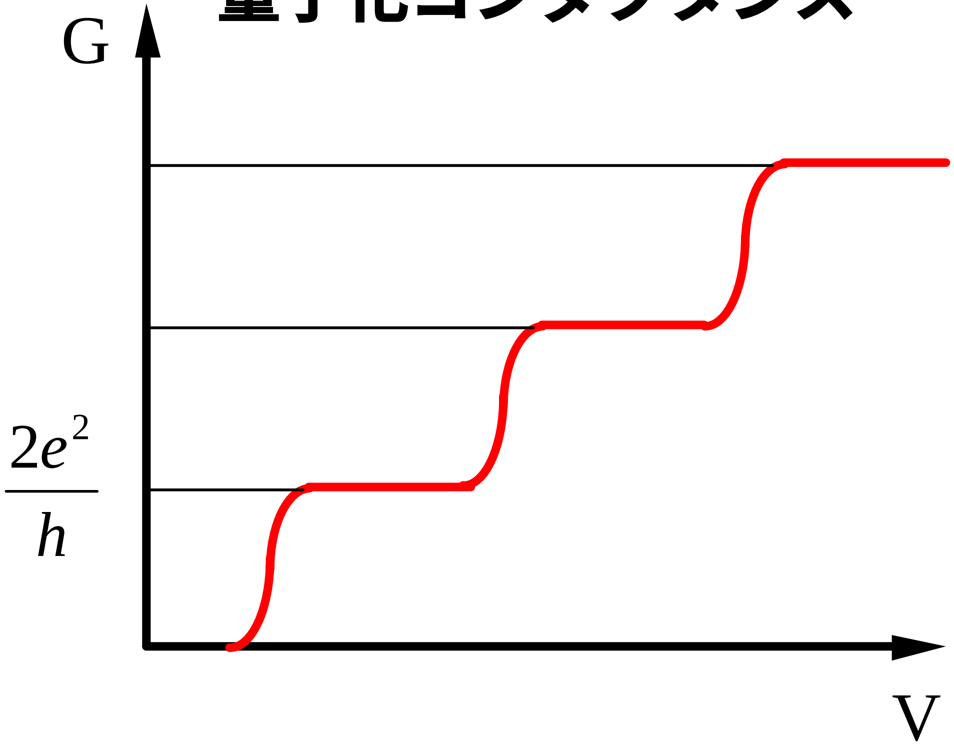
価電子帯

伝導帯

1次元量子構造 の特徴

量子伝導
- 抵抗が長さによらず一定
- 量子抵抗を示す
- 散乱がない　バリスティック

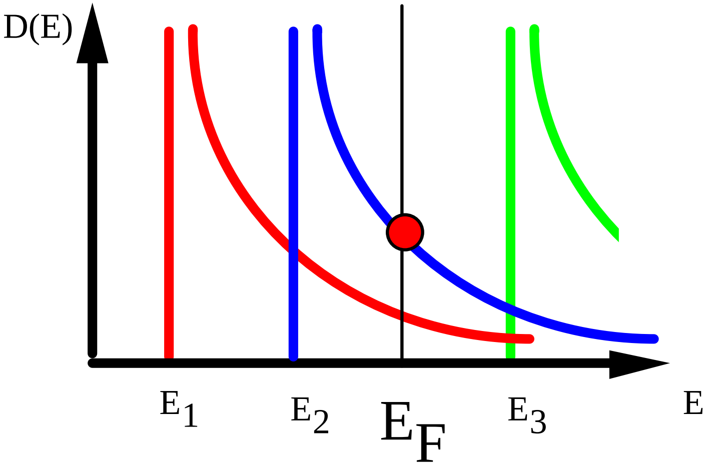



量子化コンダクタンス

一次元量子細線中を流れる電流

フェルミレベルがE_Fにある場合

$$D(E_F)=\frac{g_s}{h}\left(\frac{m}{2(E_F-E_n)}\right)^{\frac{1}{2}}$$



電子の速度は $E=\frac{1}{2}mv^2$ **より**

$$v(E_F)=v_F=\sqrt{\frac{2E}{m}}=\left(\frac{2(E_F-E_n)}{m}\right)^{\frac{1}{2}}$$

n**番めのサブバンドを流れる電流は**

$$I=e\bullet D(E_F)\bullet v_F\bullet eV=e\times\frac{g_s}{h}\left(\frac{m}{2(E_F-E_n)}\right)^{\frac{1}{2}}\times\left(\frac{2(E_F-E_n)}{m}\right)^{\frac{1}{2}}\times eV=\frac{g_s e^2}{h}V$$

$$G=\frac{I}{V}=\frac{g_s e^2}{h}=\frac{2e^2}{h}$$

→ **量子化コンダクタンス：一定**

n番めまでの全サブバンドを流れる全電流は

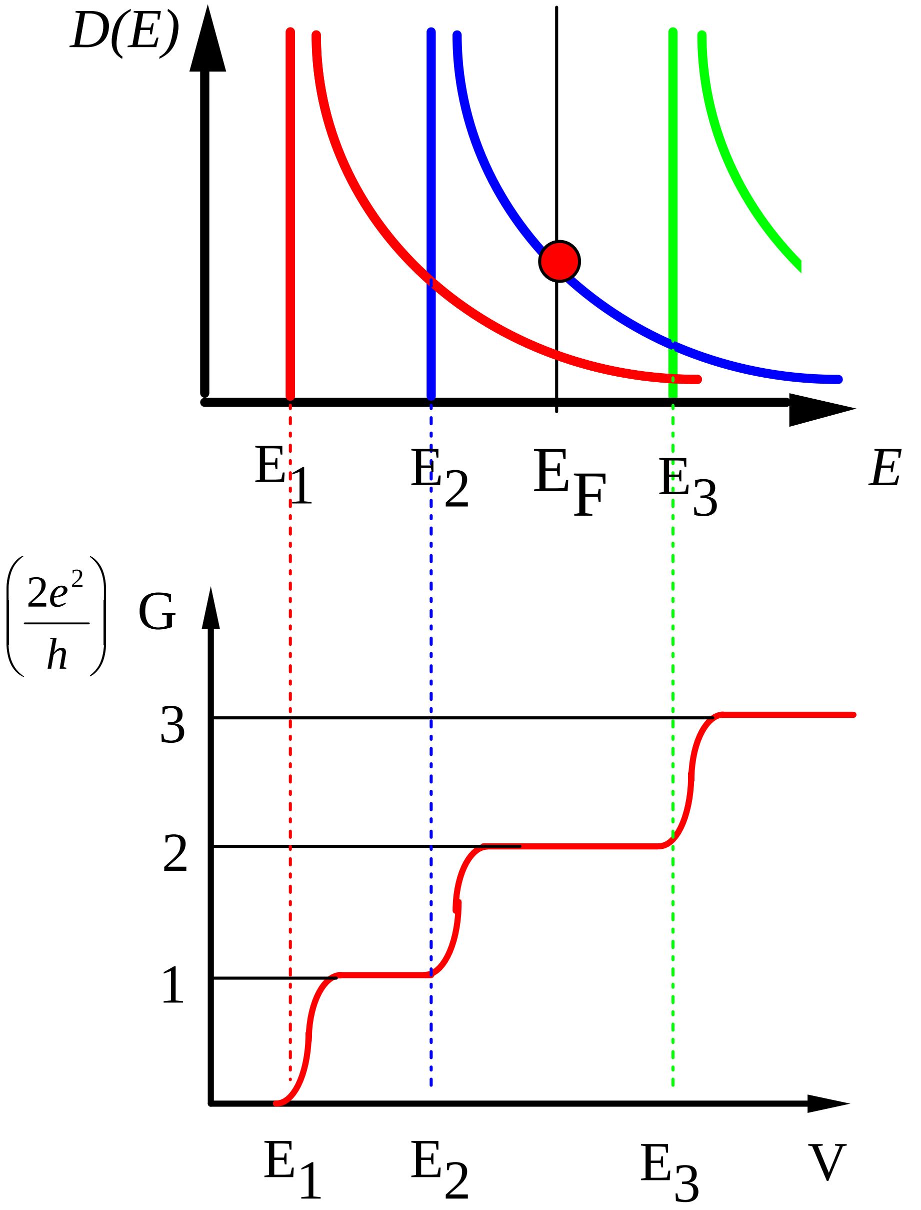
$$I = \sum_{i=1}^{i=n} \frac{2e^2}{h} V$$

$$= n \frac{2e^2}{h} V$$

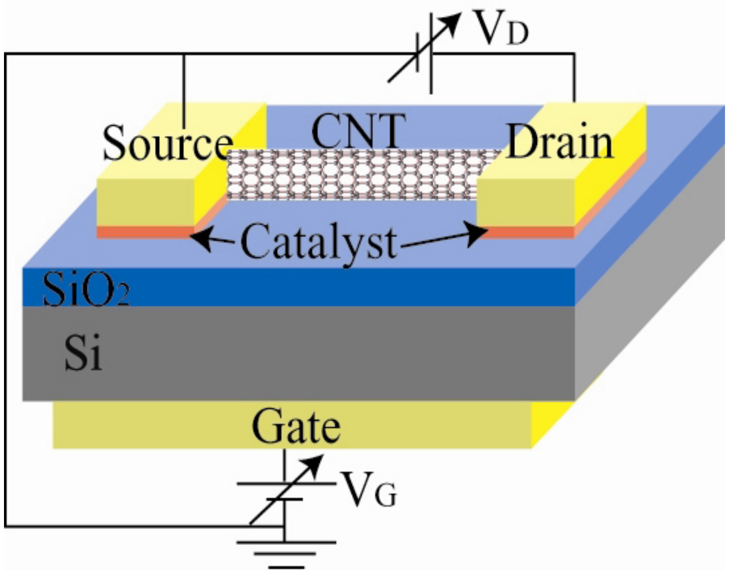
$$G = \frac{I}{V} = \frac{2e^2}{h}$$

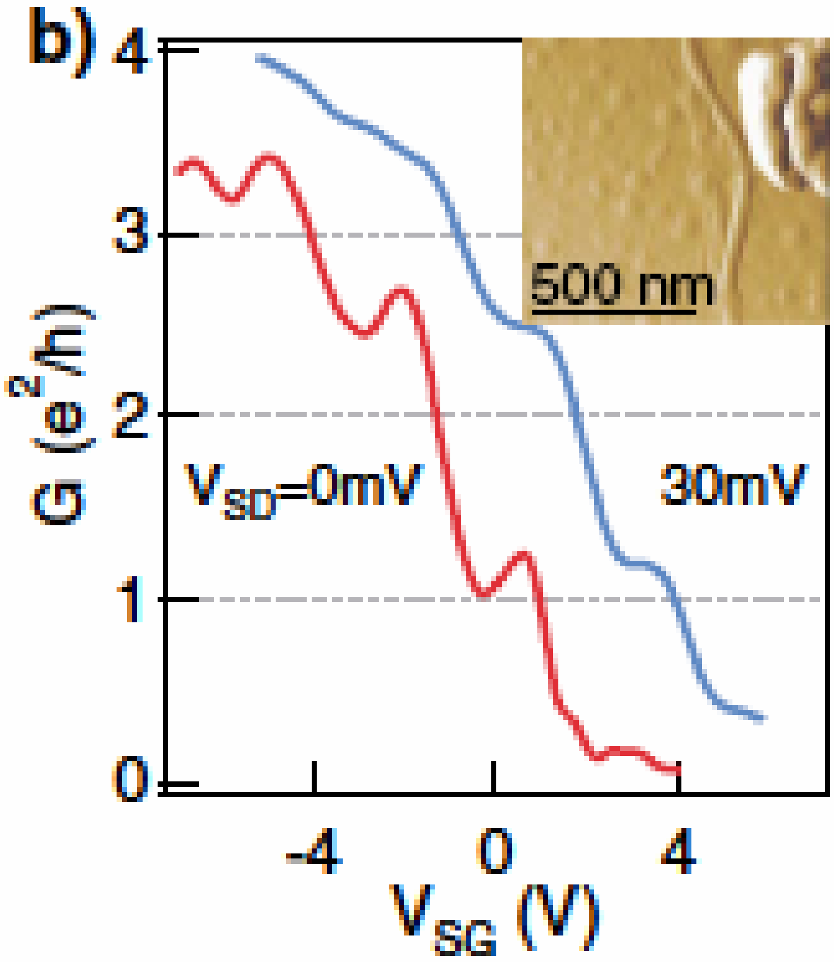
量子コンダクタンス：一定

細線の長さに依存しない！！



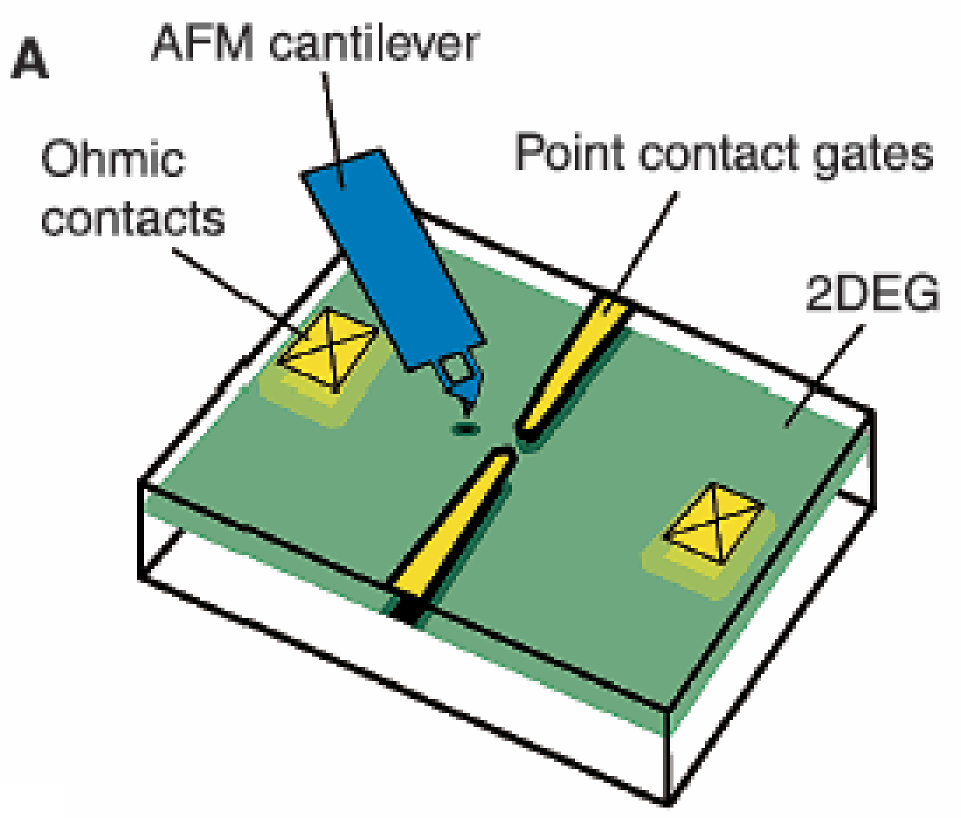
カーボンナノチューブの量子伝導

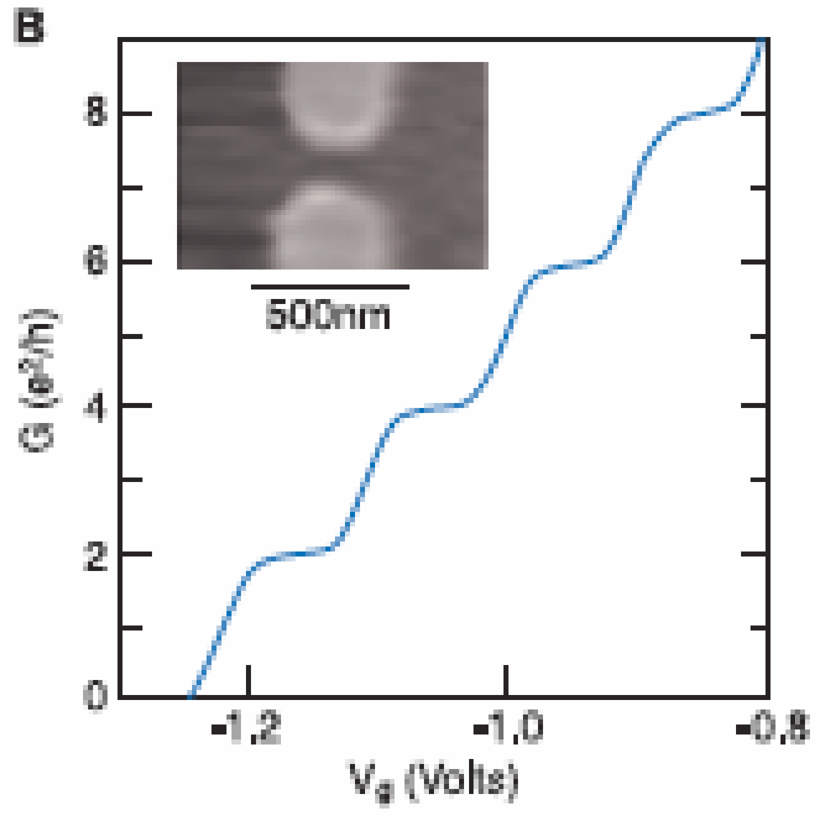




1次元量子コンダクタンスの観察

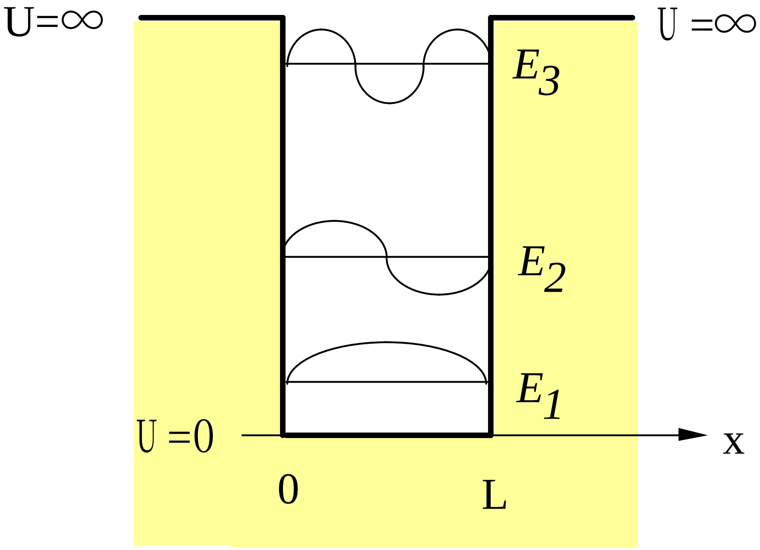
R. M. Westervelt
Science 2000 289 2323
Nature 410 183 2001





量子井戸のエネルギー準位

$$-\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2}+U(x)\varphi=E\varphi$$



$$\varphi=C\sin(kx)=C\sin(\frac{n\pi}{L}x)$$

波数 $k=\frac{n\pi}{L}$

$$E_3=\frac{9}{8m}\frac{h^2}{L_x^2}$$

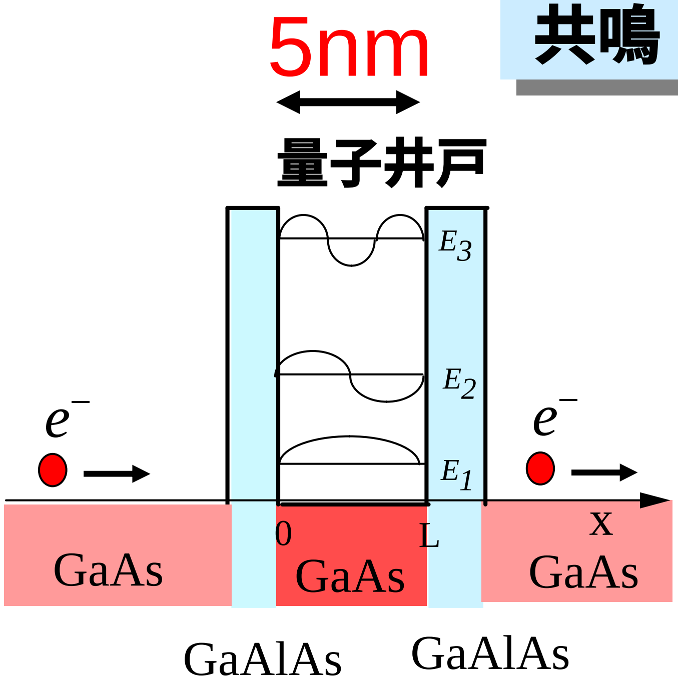
$$E_2=\frac{4}{8m}\frac{h^2}{L_x^2}$$

$$E_1=\frac{1}{8m}\frac{h^2}{L_x^2}$$

エネルギー準位を表す式

$$\boxed{E_n=\frac{\hbar^2k^2}{2m}}=\frac{h^2}{8\pi^2m}\left(\frac{n\pi}{L}\right)^2=\frac{n^2h^2}{8mL^2}$$

共鳴トンネルダイオード



電子の定在波は見えるか？

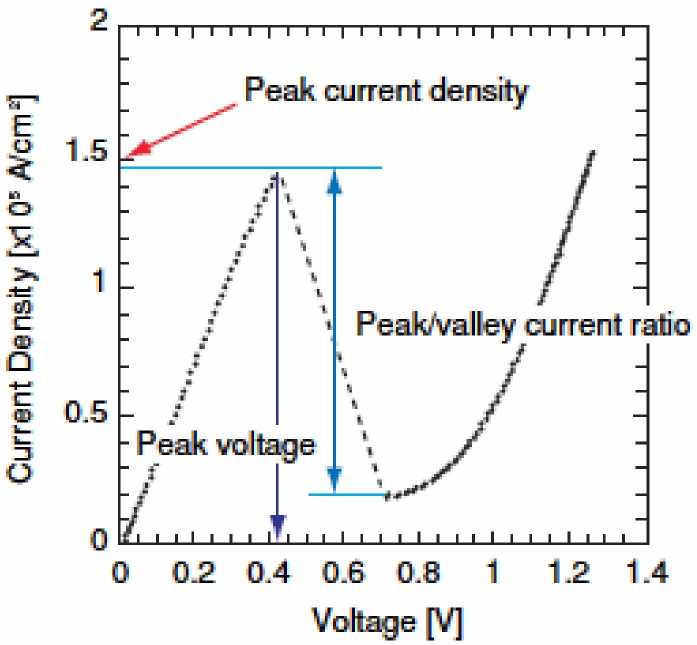
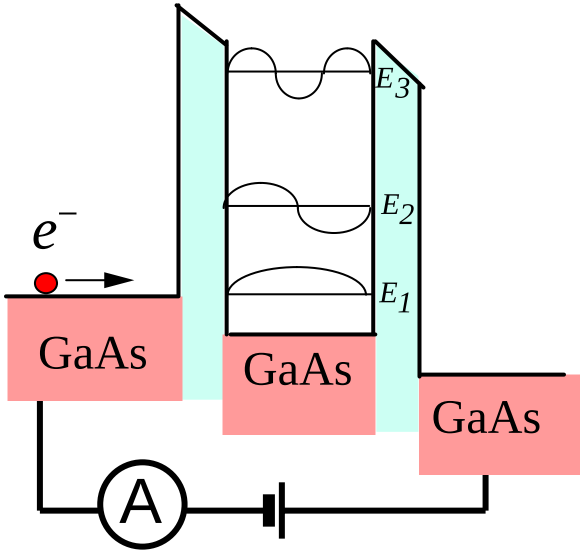
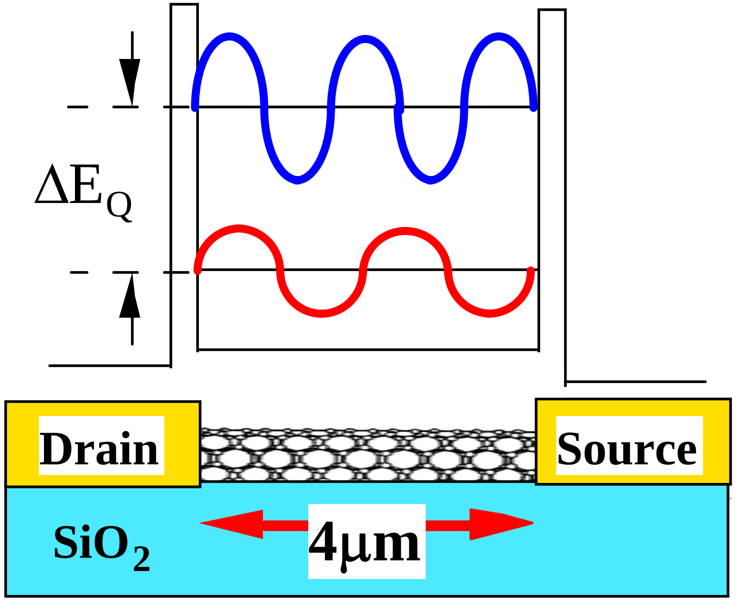


図１　MOVPE 成長 InP-RTD の電流電圧特性



カーボンナノチューブにおける 正孔のコヒーレント伝導

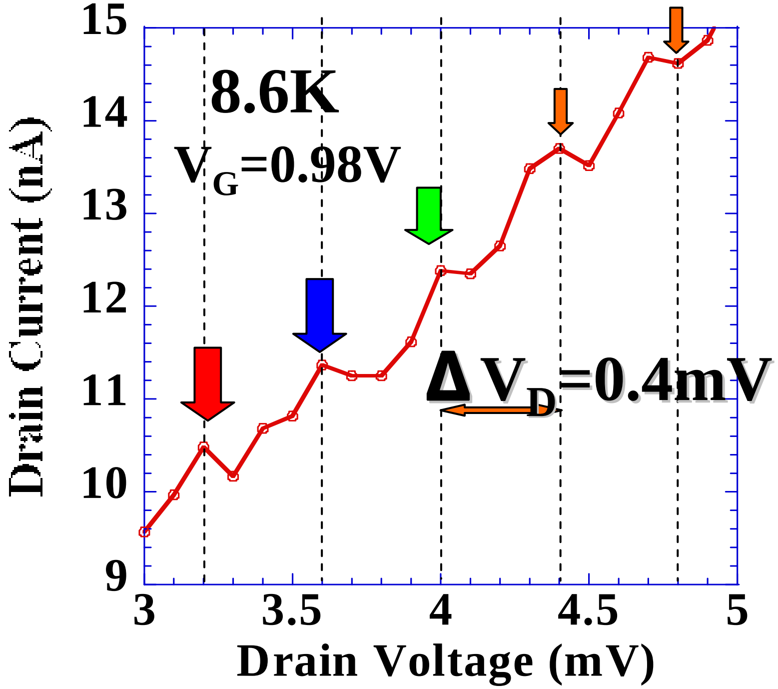
Discrete Energy Level



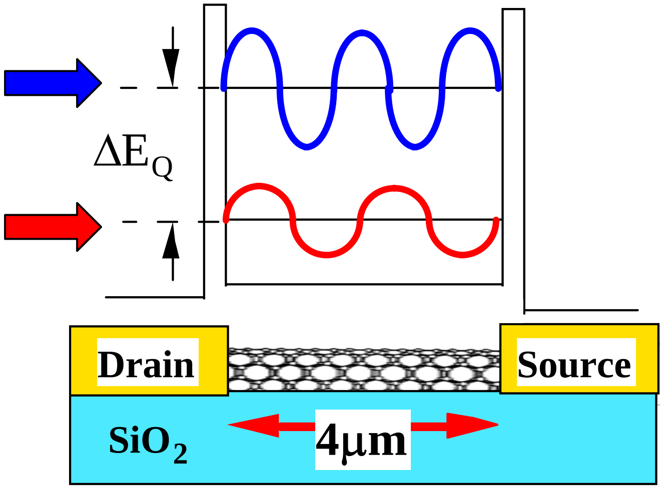
正孔が波の性質を4μmにわたって保つ

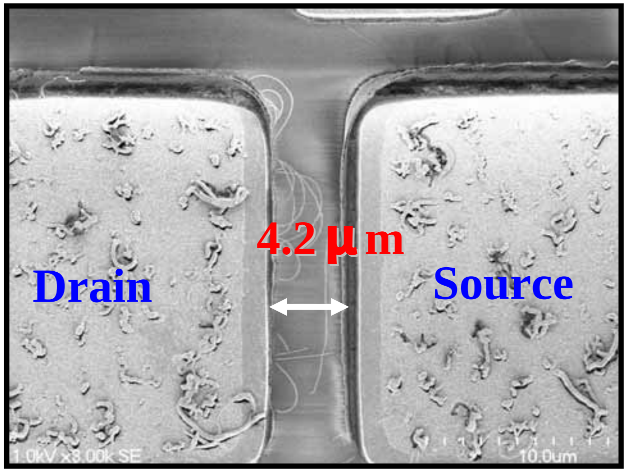
- ・4μmにわたる量子準位の形成
- ・4μmにわたる正孔のコヒーレント伝導

カーボンナノチューブ内の量子準位／共鳴トンネル



Discrete Energy Level

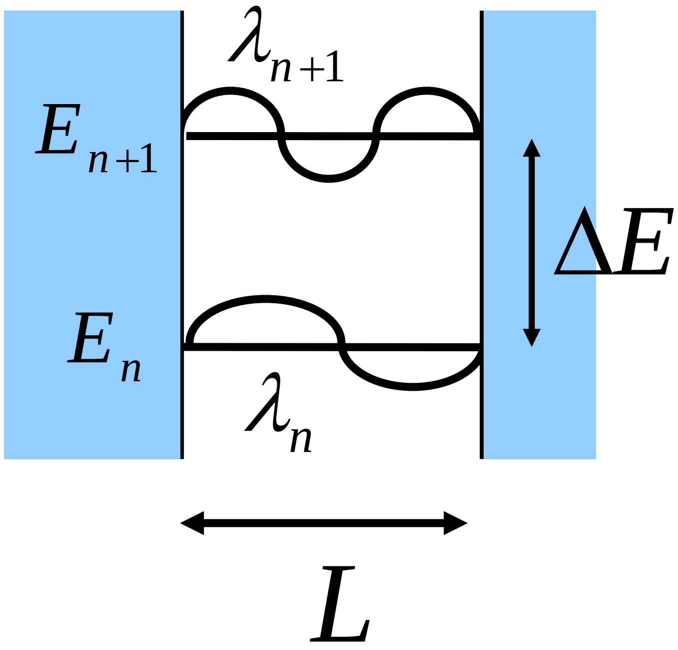




n番目と n+1番目の量子準位のエネルギー差 $\varDelta E$ と 井戸幅 L

$$E_n = h\nu_n = \frac{hv_F}{\lambda_n}$$

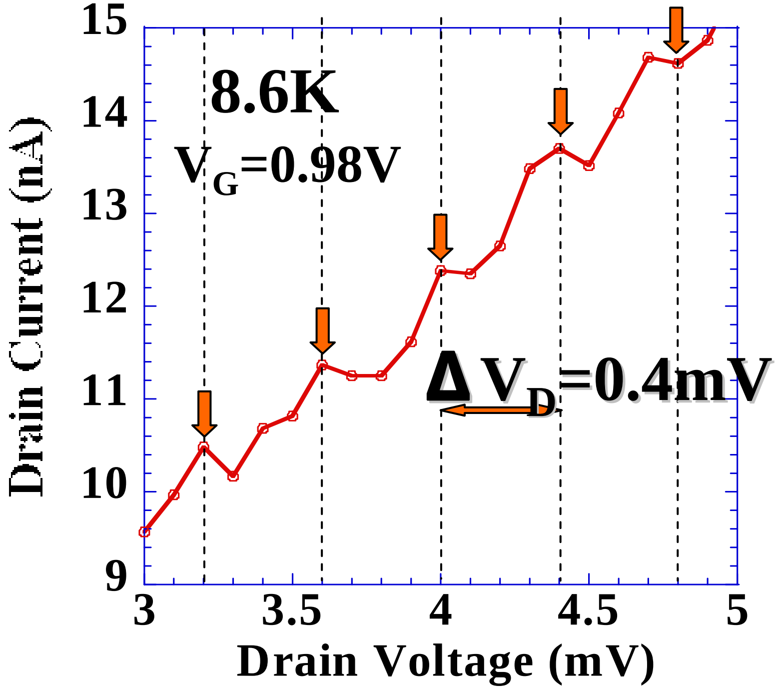
$$E_{n+1} = h\nu_{n+1} = \frac{hv_F}{\lambda_{n+1}}$$

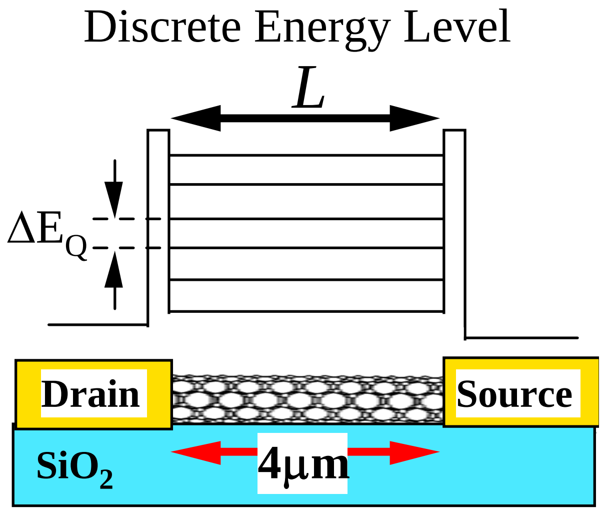


$$\underline{\Delta E} = E_{n+1} - E_n = \frac{hv_F}{\lambda_{n+1}} - \frac{hv_F}{\lambda_n}$$

$$= \frac{hv_F(n+1)}{2L} - \frac{hv_F n}{2L} = \frac{hv_F}{2\underline{L}}$$

Resonant Tunneling of Hole through Quantum Level in Carbon Nanotube → Negative Conductance





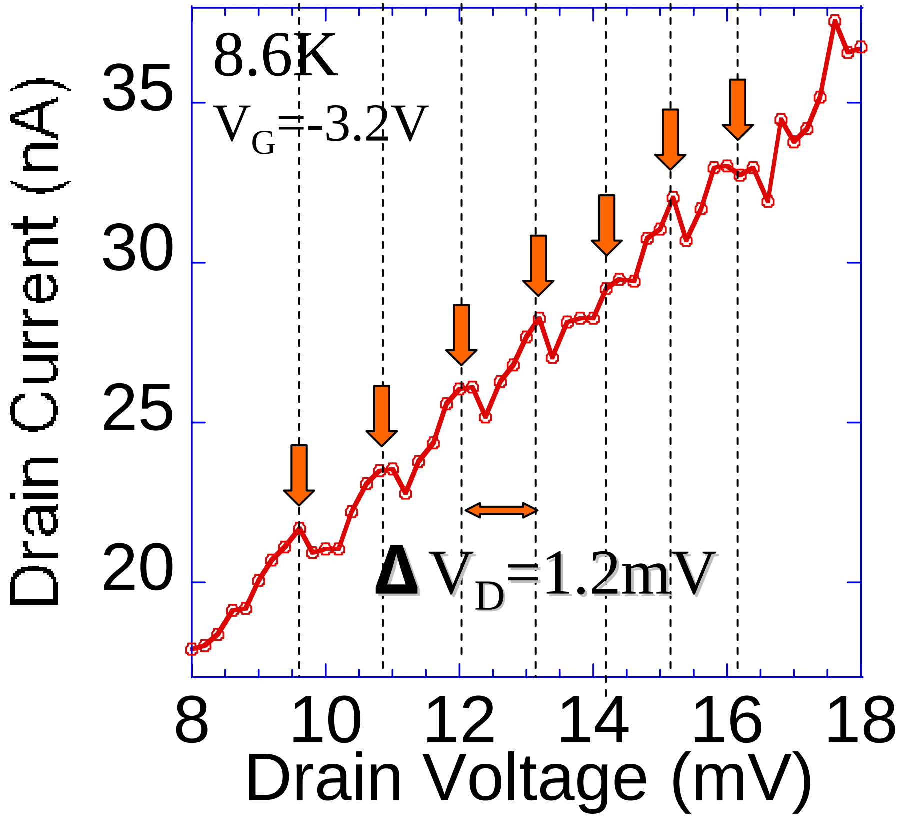
$$\Delta V_D \approx \Delta E \qquad \Delta E = \frac{h\nu_F}{2L}$$

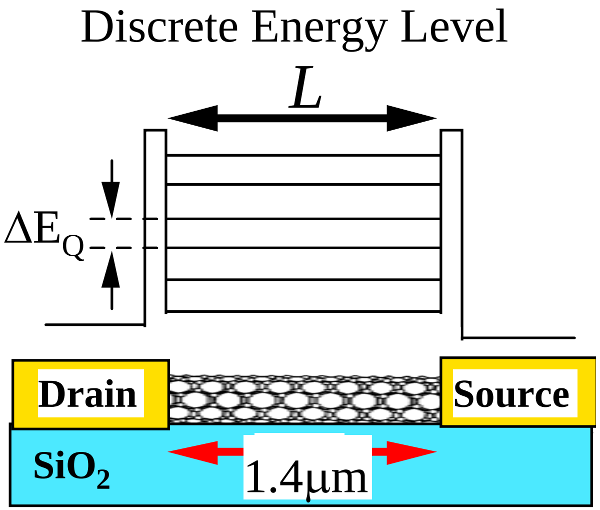
$$\underline{L = 4.2(\mu m)}$$

- h **:Plank's Constant**
- ν_F **:Fermi Velocity**
- L **:Length of CNT between Tunneling Barriers**
- e **:Elementary Charge**

L : $\frac{1.4\mu m}{4.5\mu m} \approx \frac{1}{3}$ → ΔE **3倍？**

Resonant Tunneling of 1.4μm CNT through Quantum Well





$$L = 1.4(\mu m)$$

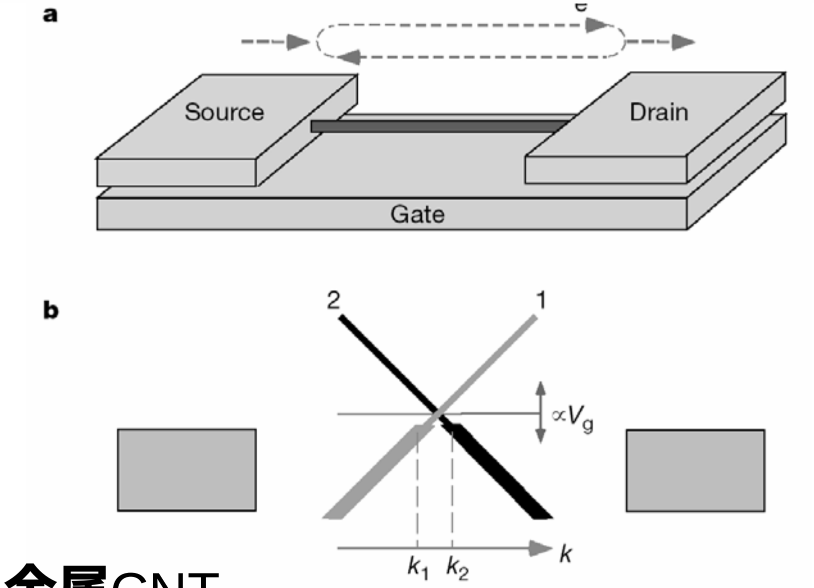
$$\Delta E \approx \Delta V_D = 1.2mV$$

3倍

$$\Delta V_D : \frac{1.2mV}{0.4mV} = 3$$

金属的カーボンナノチューブにおける電子のコヒーレント伝導

W. Liang Harvard Univ.



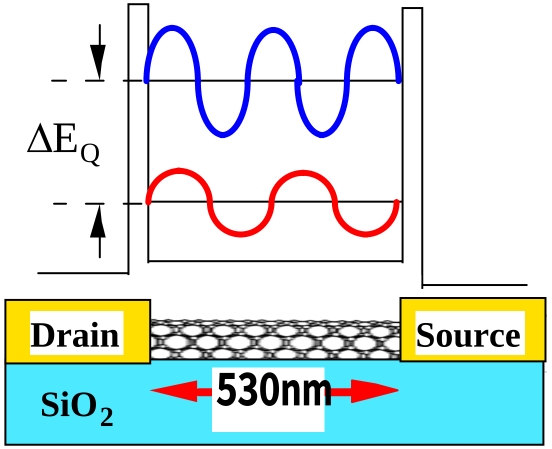
金属CNT

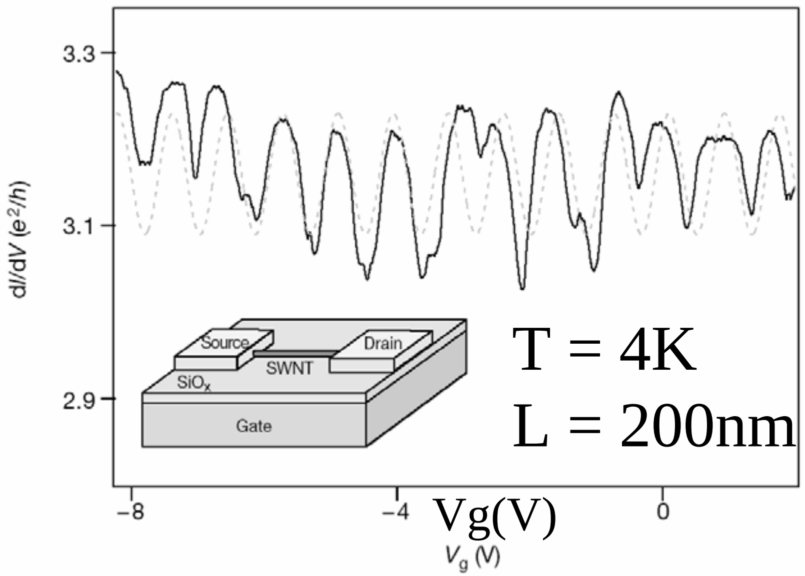
周期境界条件

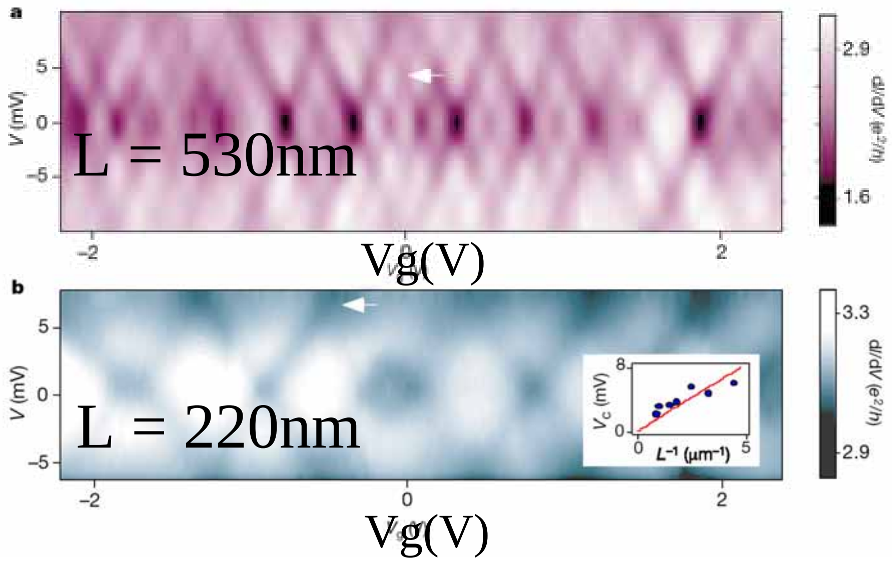
$2LeV_c/h\ v_F = 2\pi$

電子

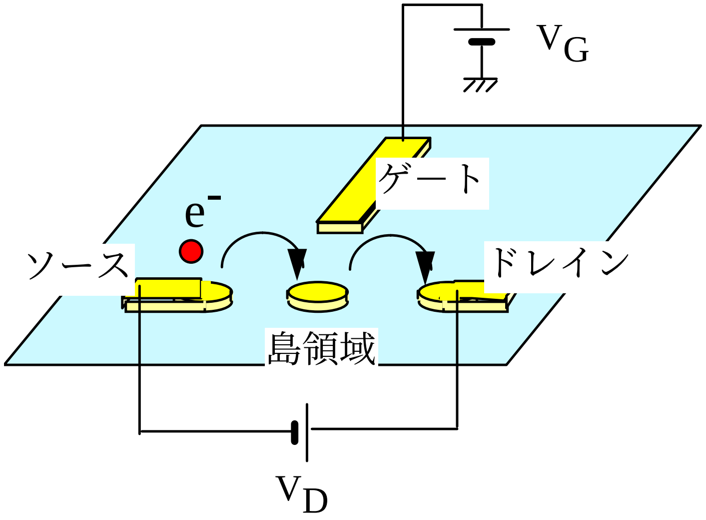
Discrete Energy Level

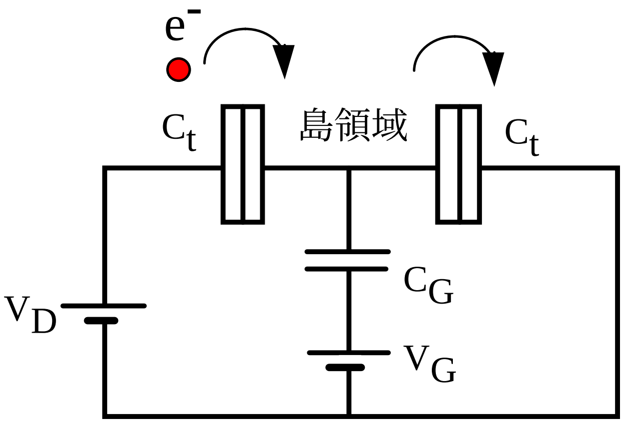


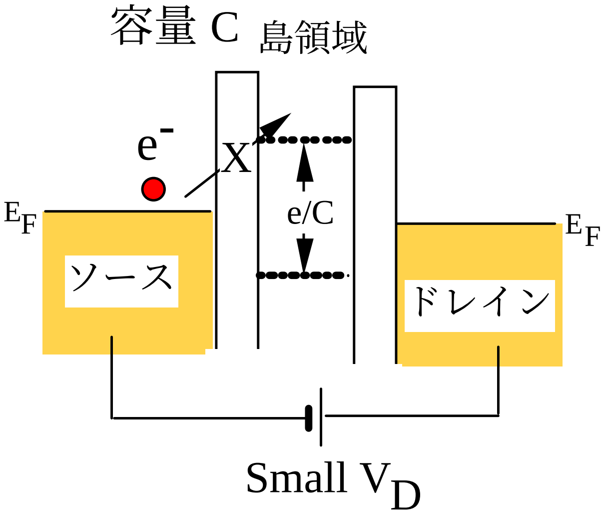




単一電子トランジスタの基本
Single Electron Transistor







$Ec = e^2 / 2C$ 一電子のクーローンエネルギー

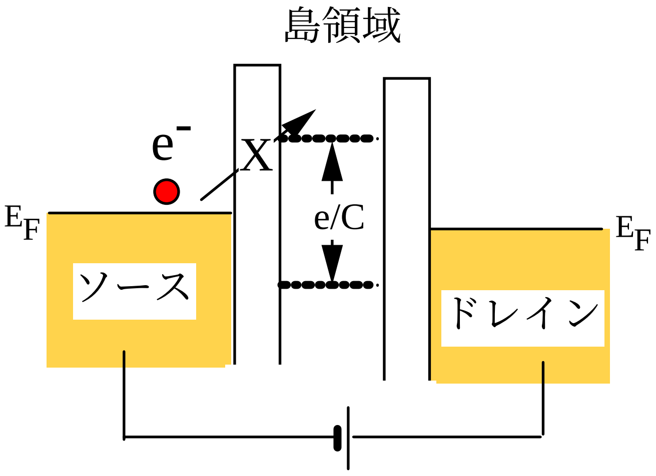
$\Delta E = (Q-e)^2/2C - Q^2/2C = Ec - eV$

$\Delta E > 0$ は禁止

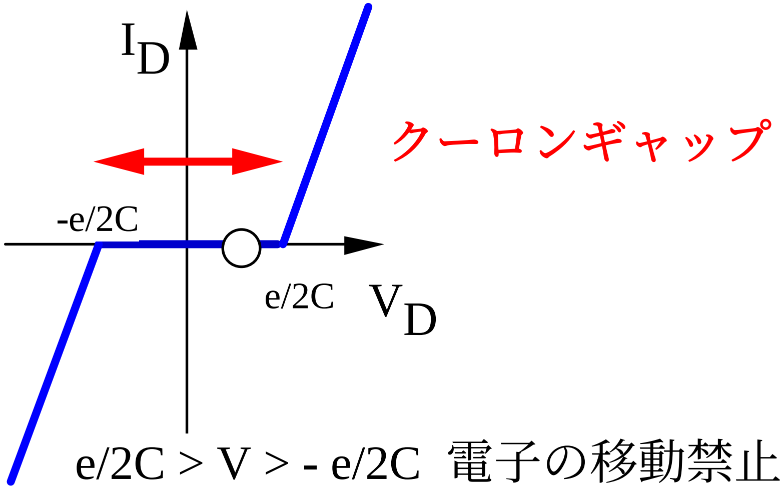
$Ec > eV \longrightarrow e/2C > V$ 電子の移動禁止

$e/2C > V > -e/2C$ 電子の移動禁止

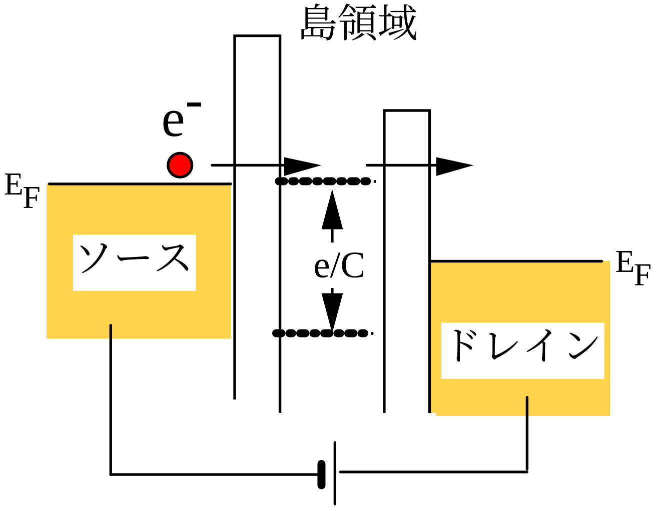
ドレイン電圧依存性



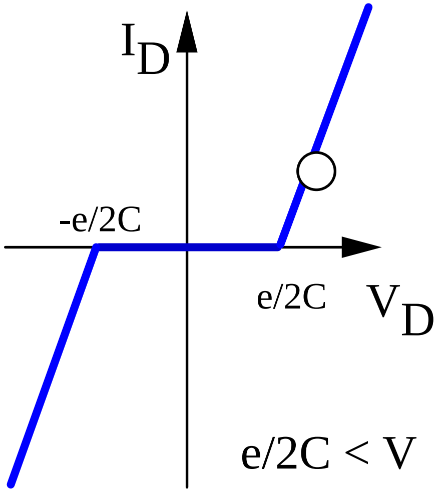
Small V_D



e/2C > V > - e/2C 電子の移動禁止



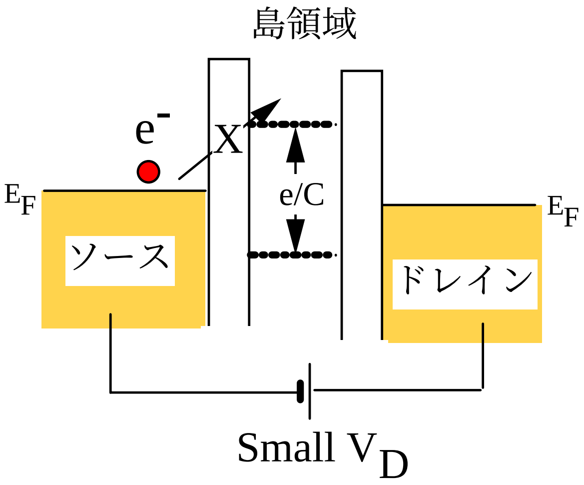
Large V_D

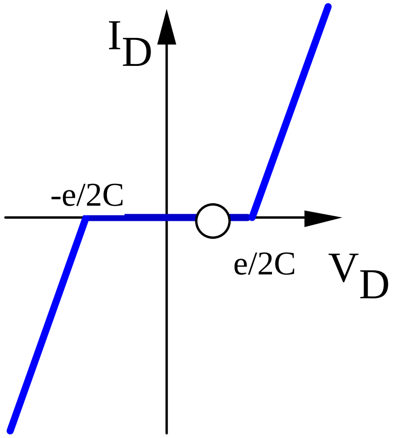


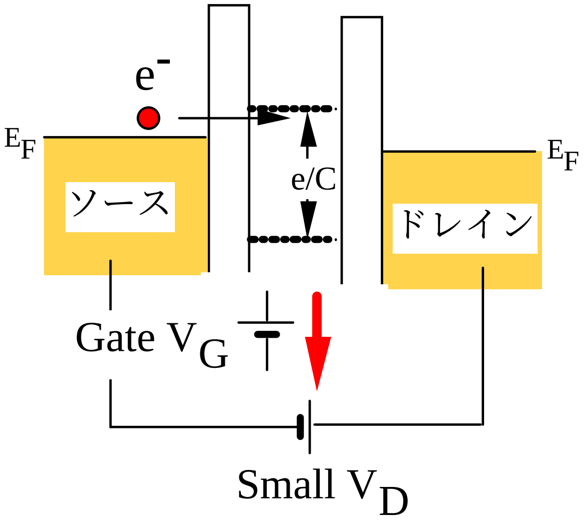
e/2C < V 電子の移動 可能

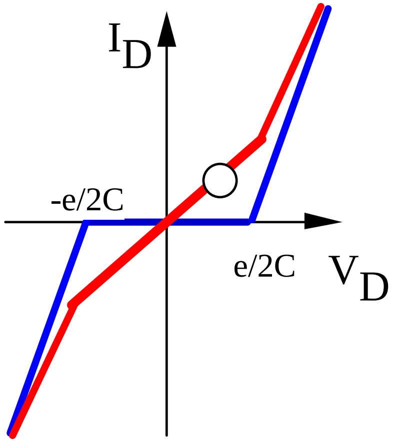
V < - e/2C 電子の移動 可能

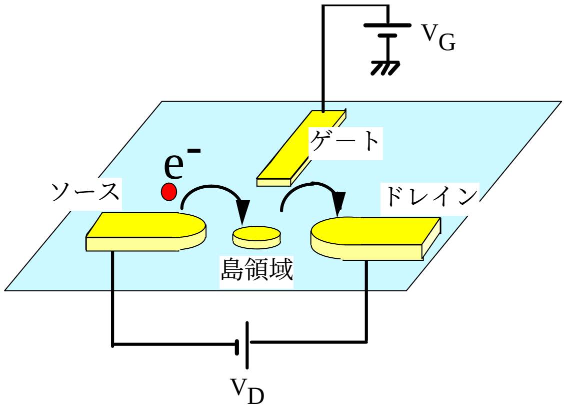
ゲート電圧依存性



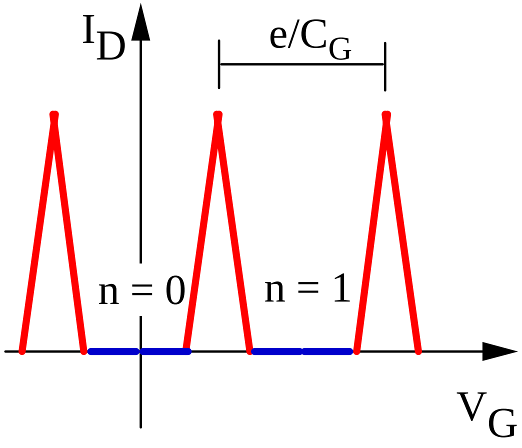




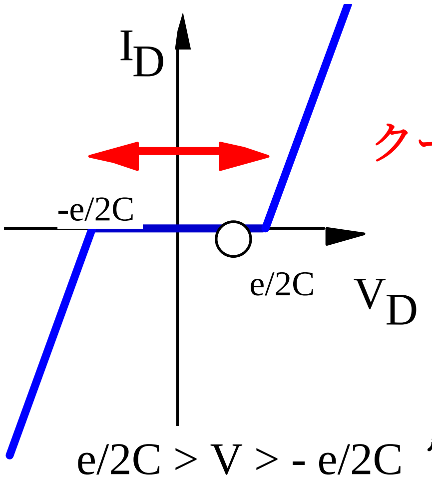




クーロン振動



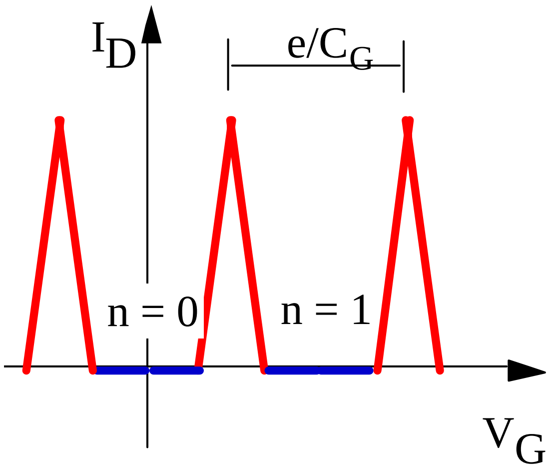
- **クーロンギャップ**
- **クーロン振動**
- **クーロンダイアモンド**

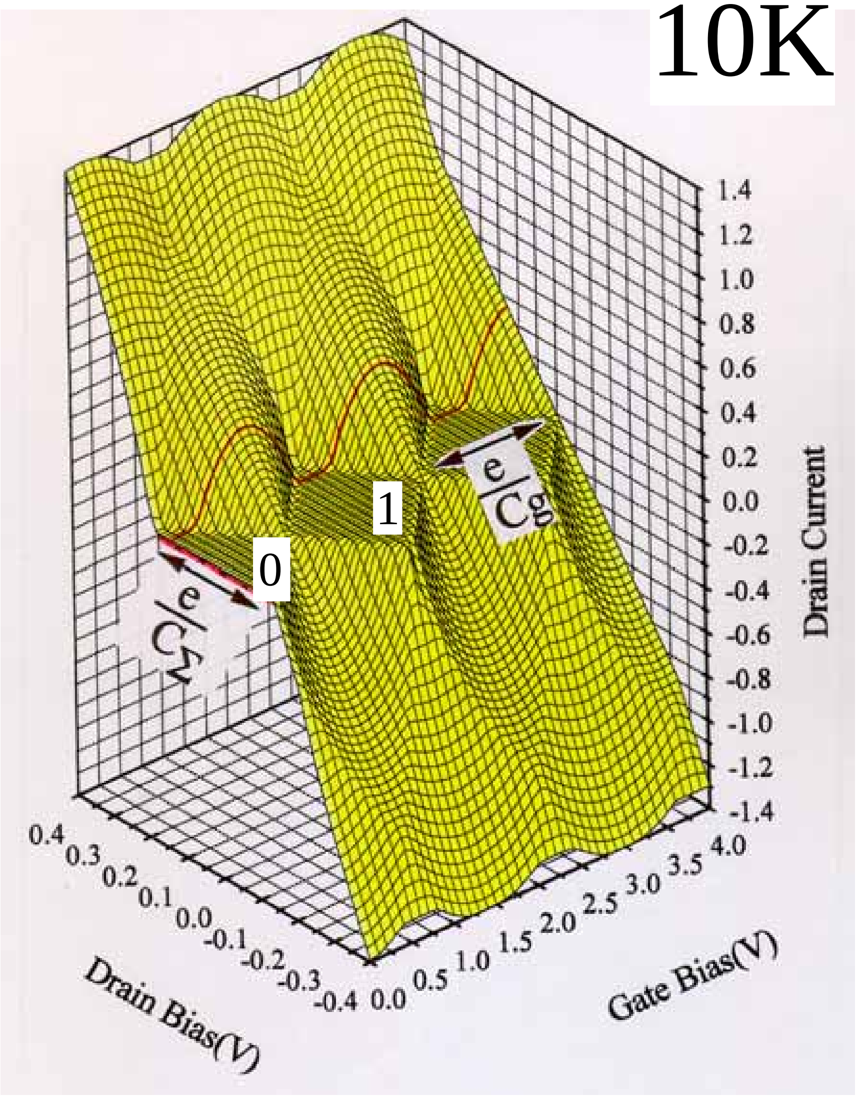


クーロンギャップ

e/2C > V > - e/2C　電子の移動禁止

クーロン振動





Tunnel Capacitance $C_1 = C_2 = 4 \times 10^{-19}$F

Gate Capacitance　$C_G = 1 \times 10^{-19}$F

クーロンブロッケードを観察するための必要条件

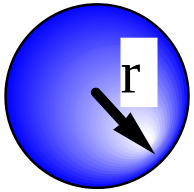
1) $kT \ll E_c = e^2/2C$ → C を小さく → 素子サイズを小さく

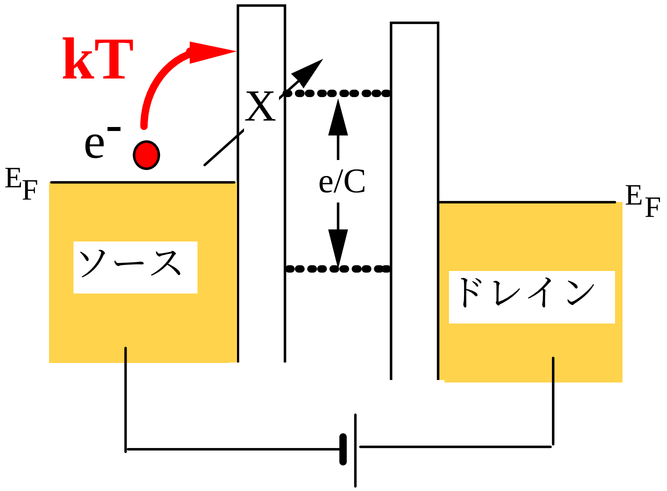
2) $R_T \gg h/e^2 = R_Q = 26\mathrm{k}\Omega$　抵抗量子

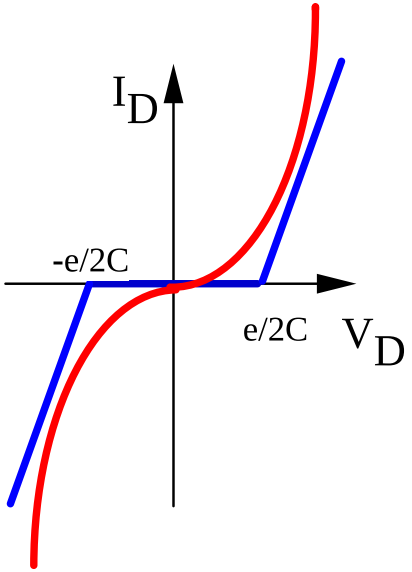
$kT = 26\mathrm{meV}$ at $300\mathrm{K}$

$E_c = e^2/2C =$ $80\mathrm{meV}$ at $C = 10^{-18}\mathrm{F}$　$r = 10\mathrm{nm}$

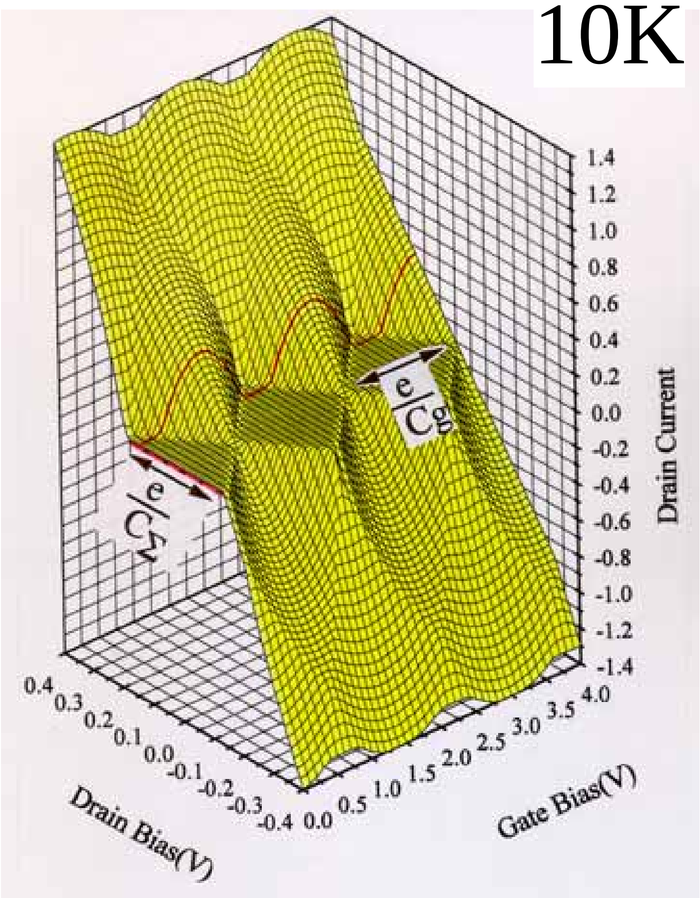
$800\mathrm{meV}$ at $C = 10^{-19}\mathrm{F}$　$r = 1\mathrm{nm}$





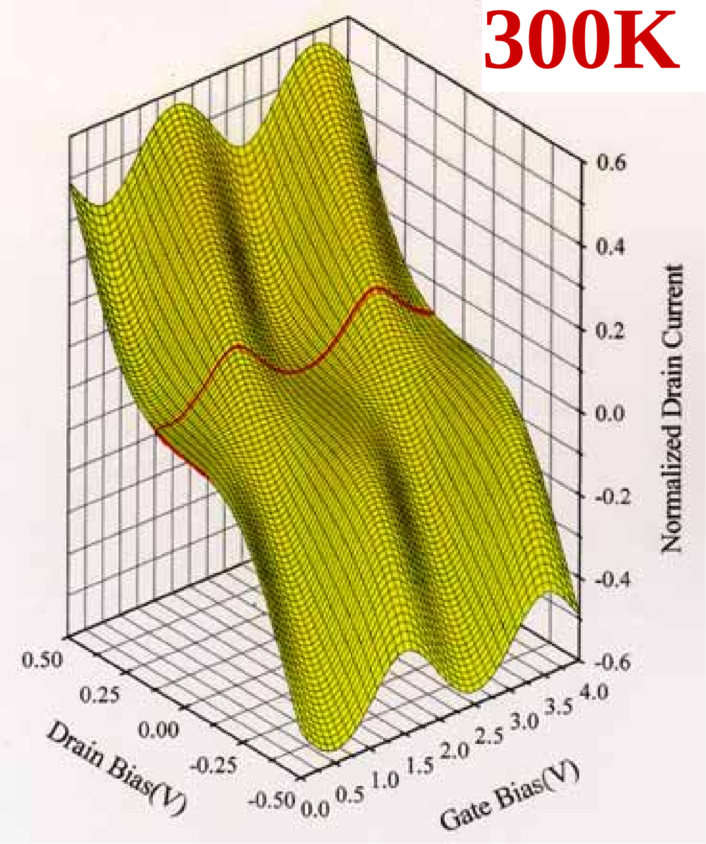


Simulated Characteristics of Single Electron Tranasistor at 10K & 300K


10K

Tunnel Capacitance $C_1 = C_2 = 4 \times 10^{-19}$F

Gate Capacitance $C_G = 1 \times 10^{-19}$F

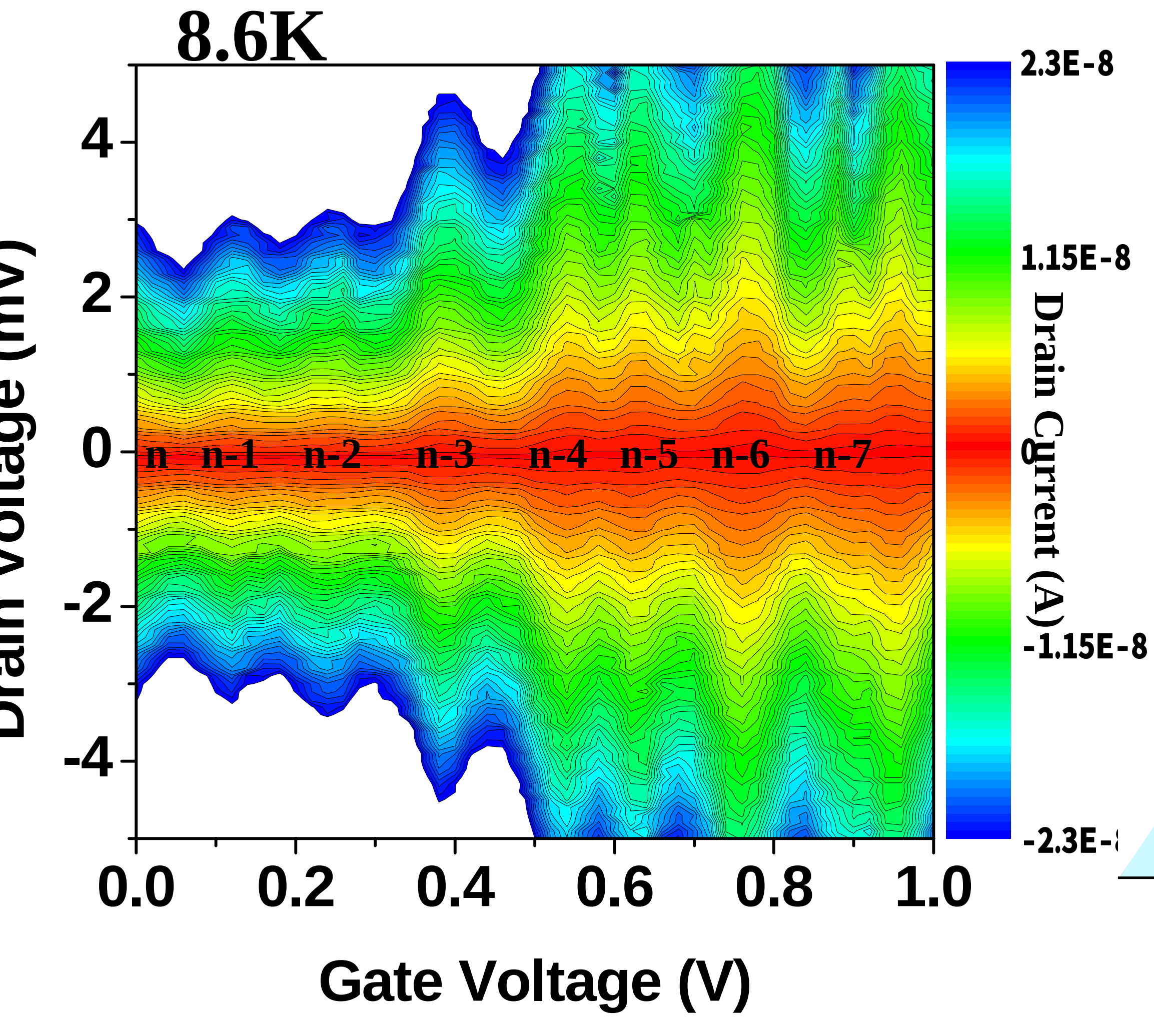

300K

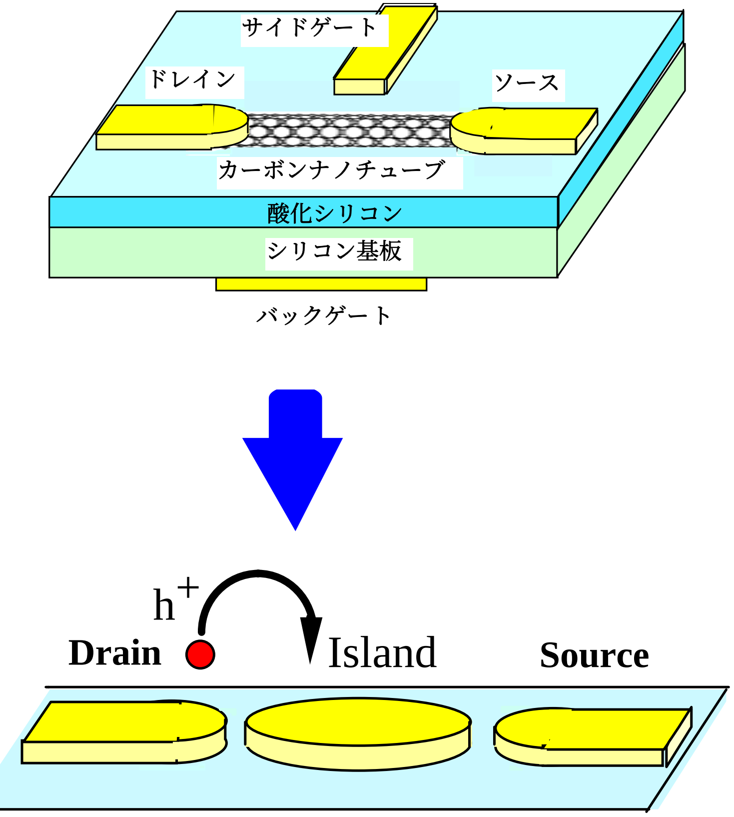
$C_{\Sigma} = C_1 + C_2 + C_G = 1.8 \times 10^{-19}$F

Tunnel Capacitance $C_1 = C_2 = 5 \times 10^{-20}$F

Gate Capacitance $C_G = 8 \times 10^{-20}$F

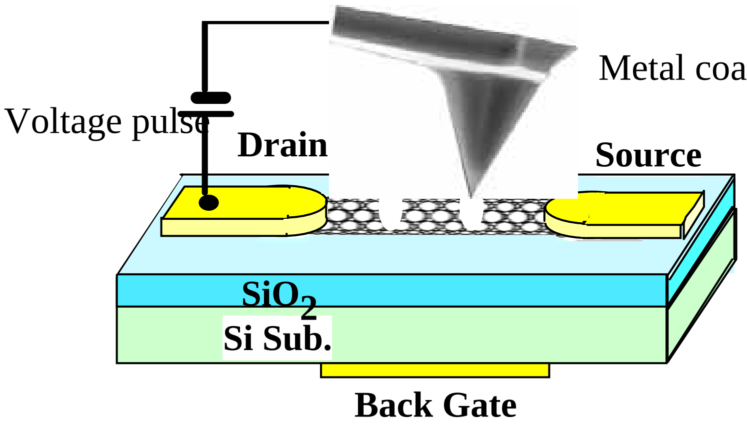
Coulomb Diamond Characteristics of Hole in Entire Carbon Nanotube Island of 4.5μm

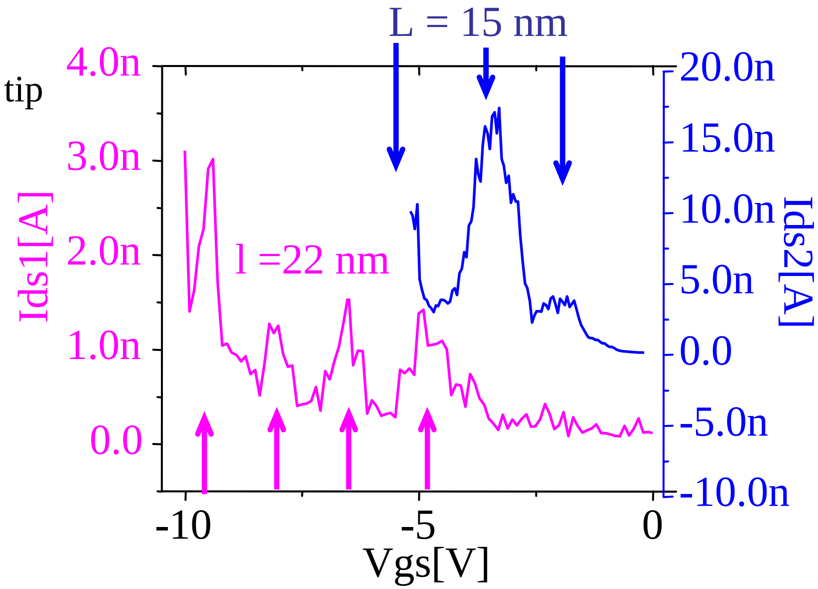


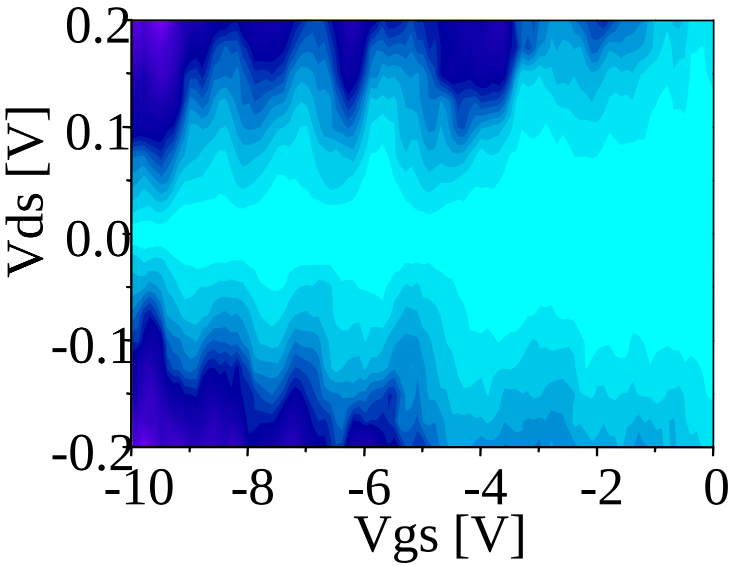


3. ④ ⑤現在の研究進捗状況と研究結果

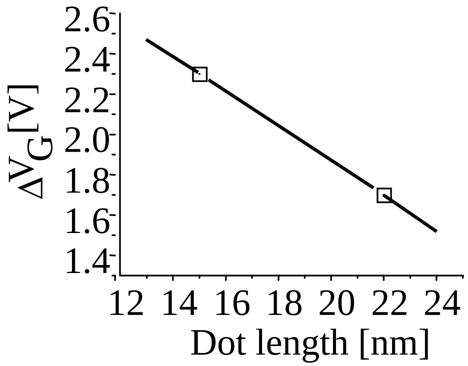
デバイス開発 5）SETの作製 ：AFM／FIBによる欠陥制御導入と室温動作

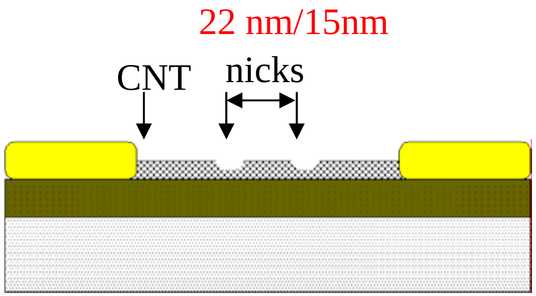






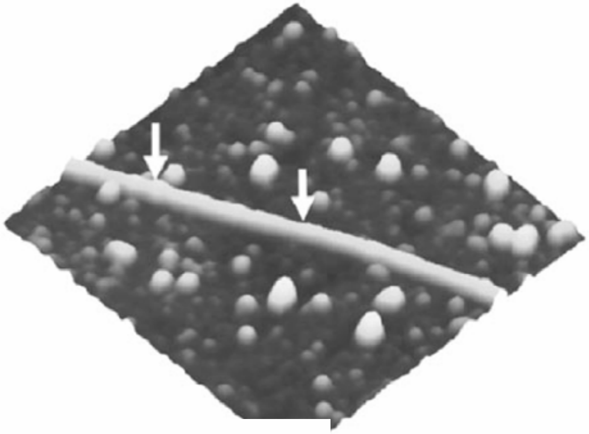
AFMでCNTに人工的に欠陥を導入して室温動作に成功

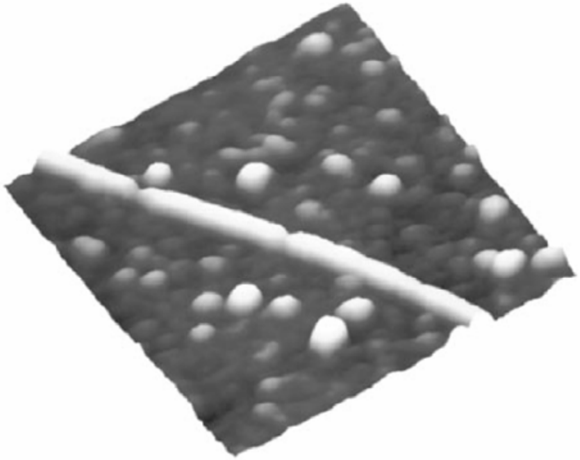


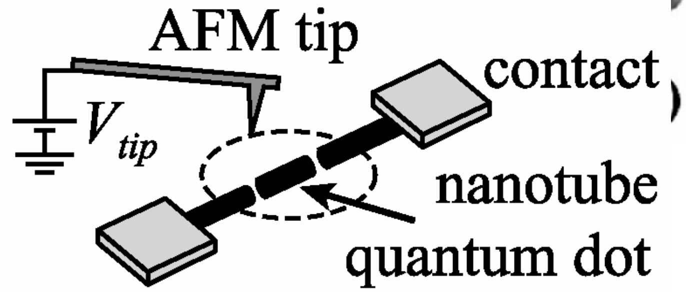


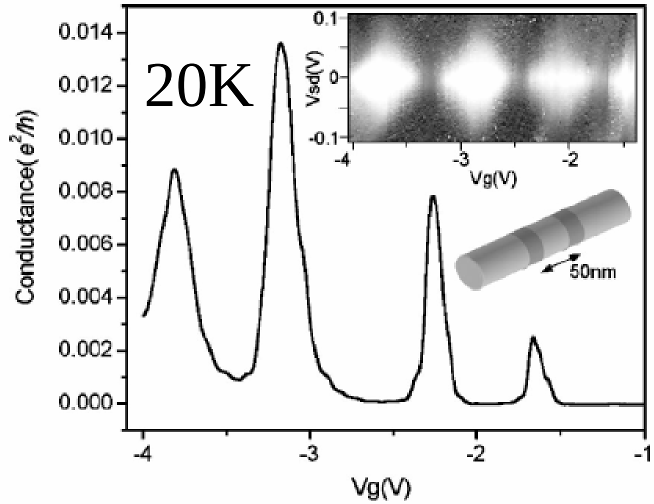
島領域のサイズ変化に対応したクーロン振動の周期変化

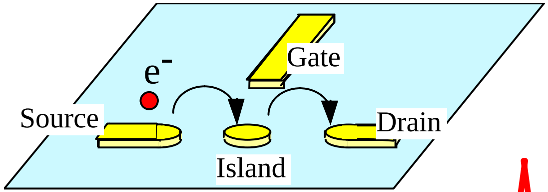
CNT Single Electron Transistor by AFM Nicking



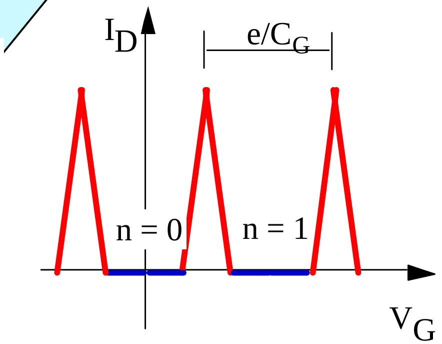


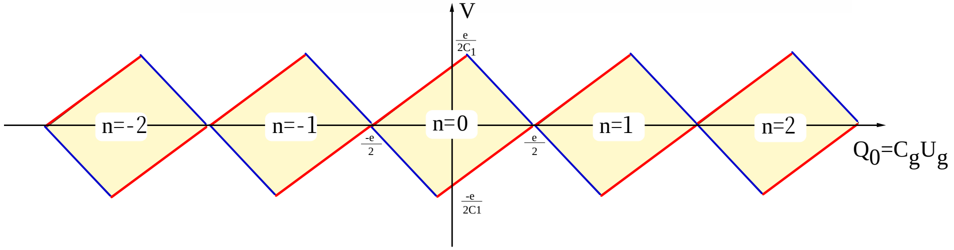




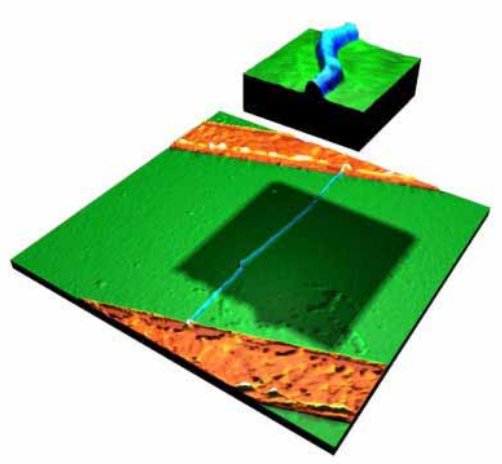


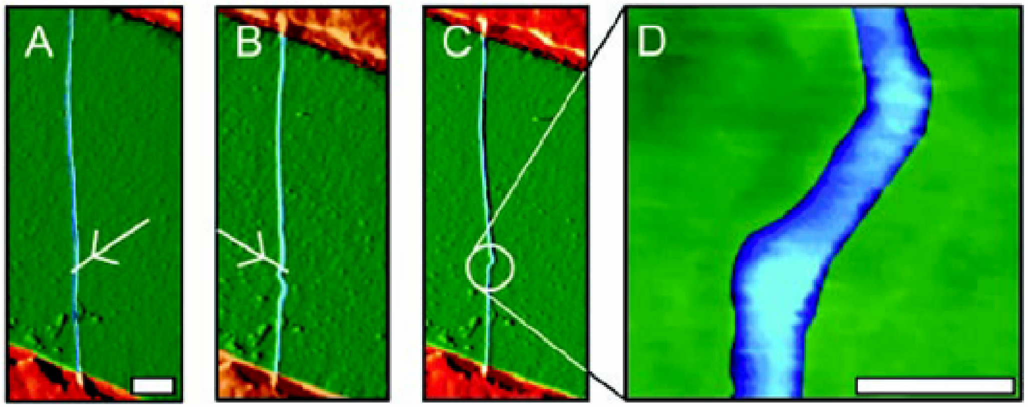
クーロン振動

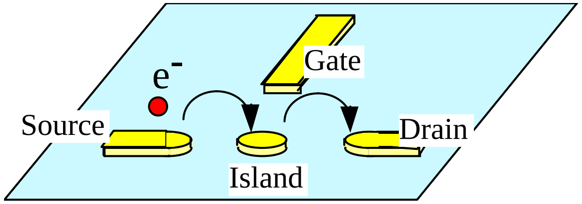


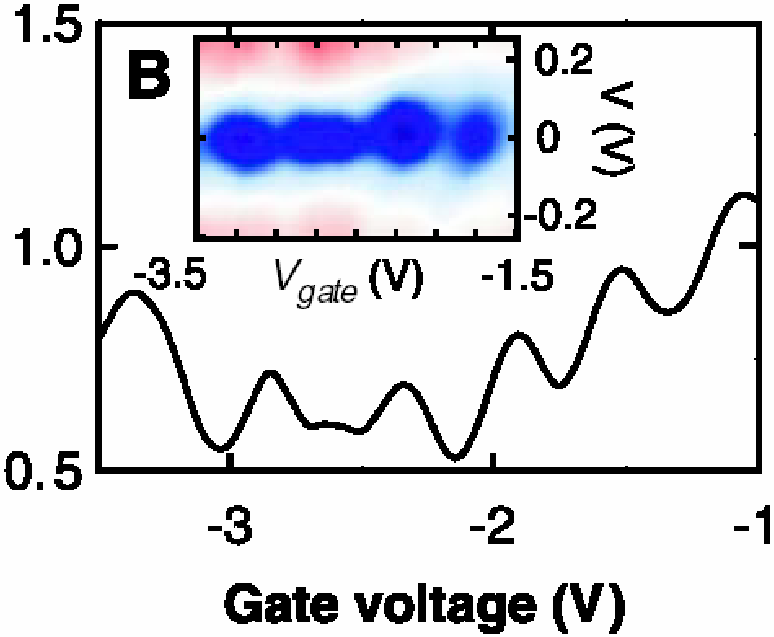


CNT Single Electron Transistor by AFM Twisting

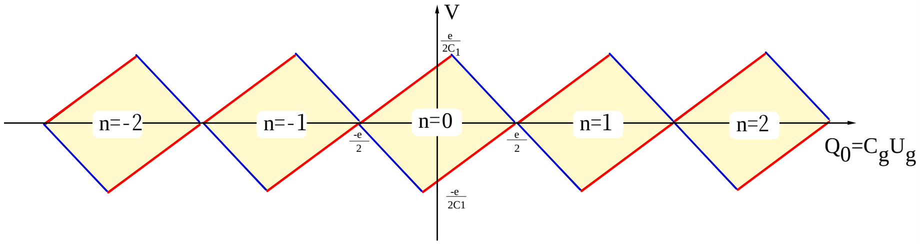




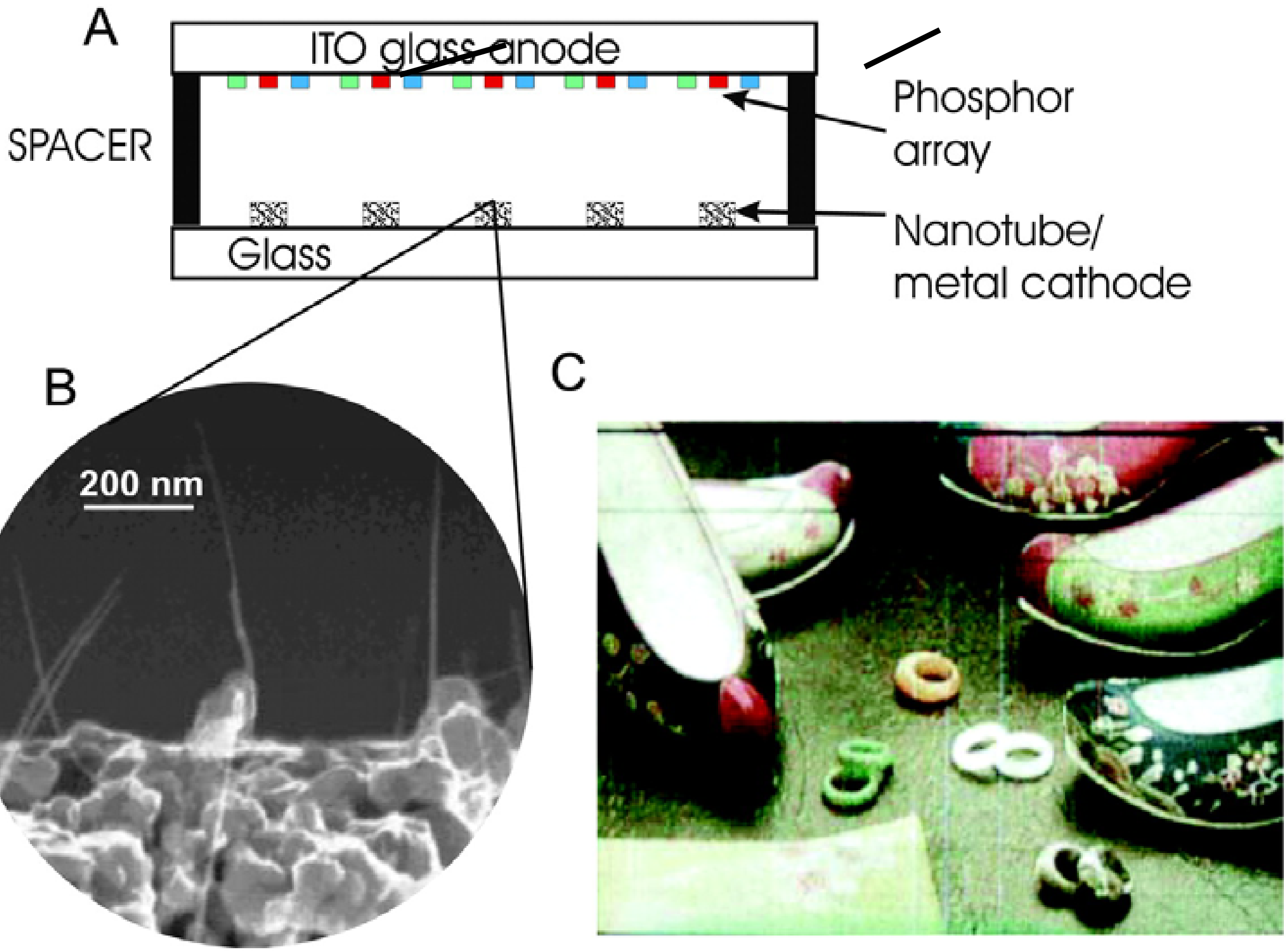




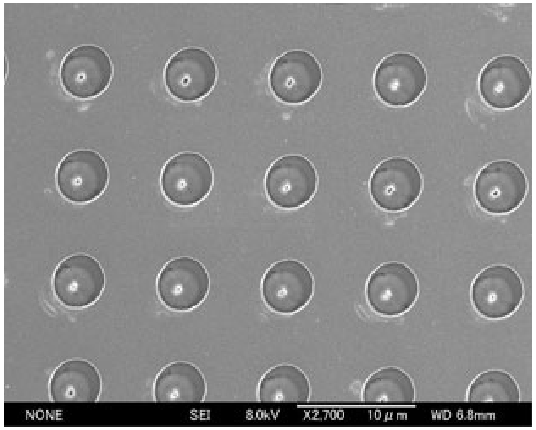
300K

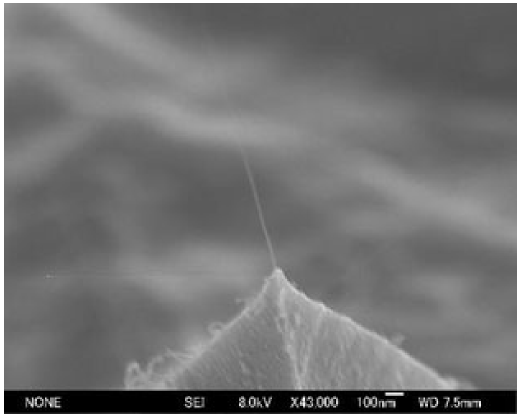


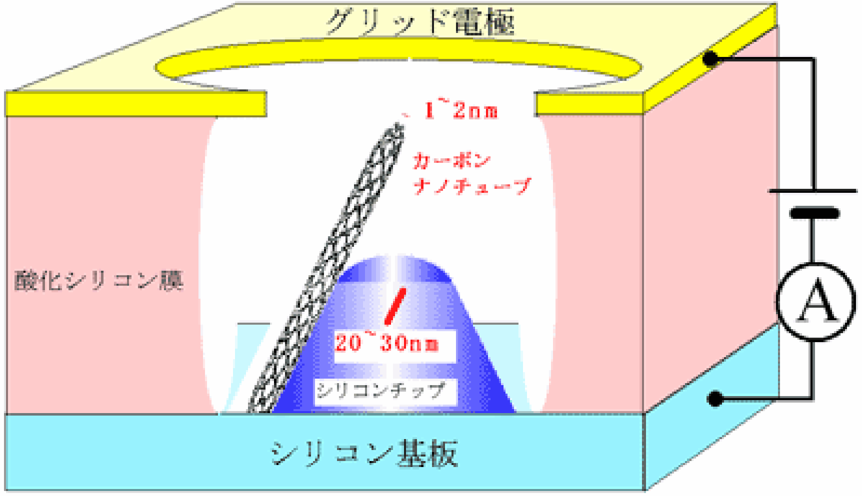
フィールドエミッタ ディスプレイ

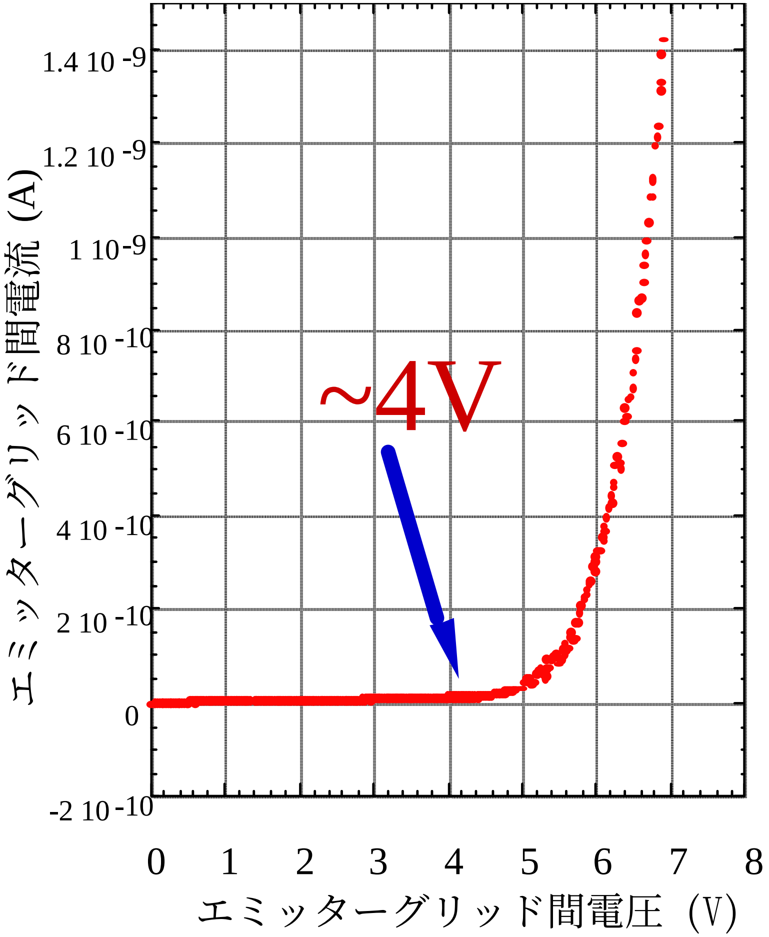


低電圧動作 カーボンナノチューブ フィールドエミッタ

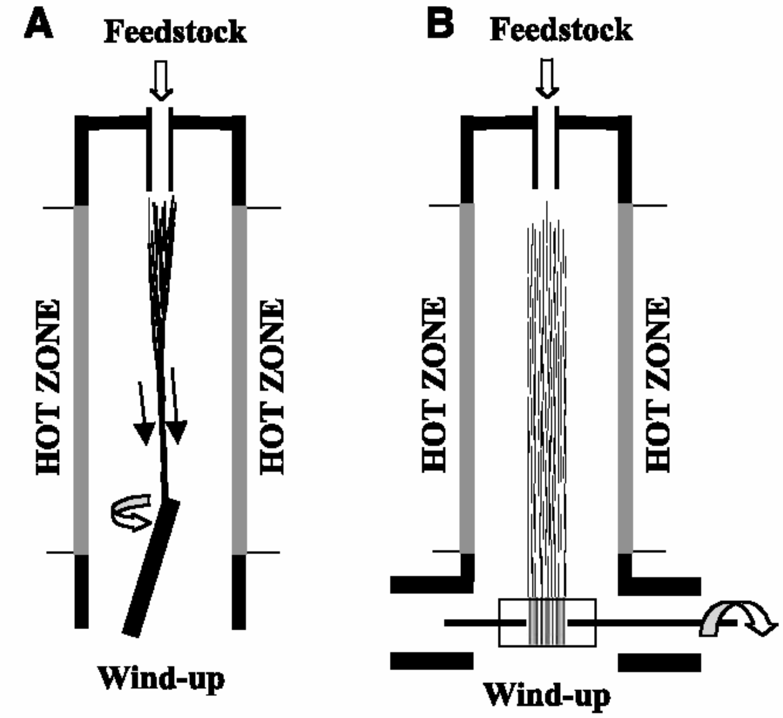


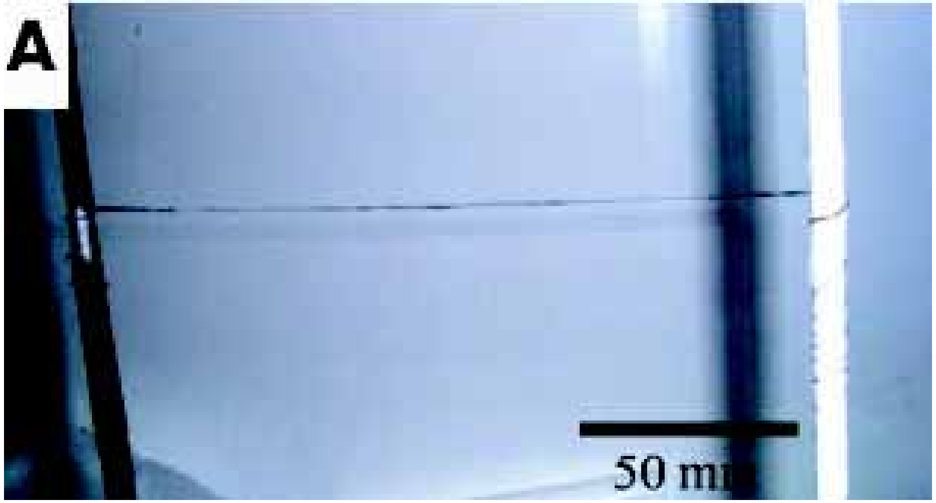


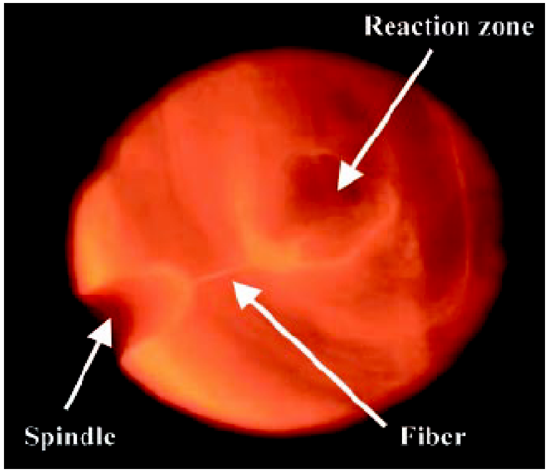


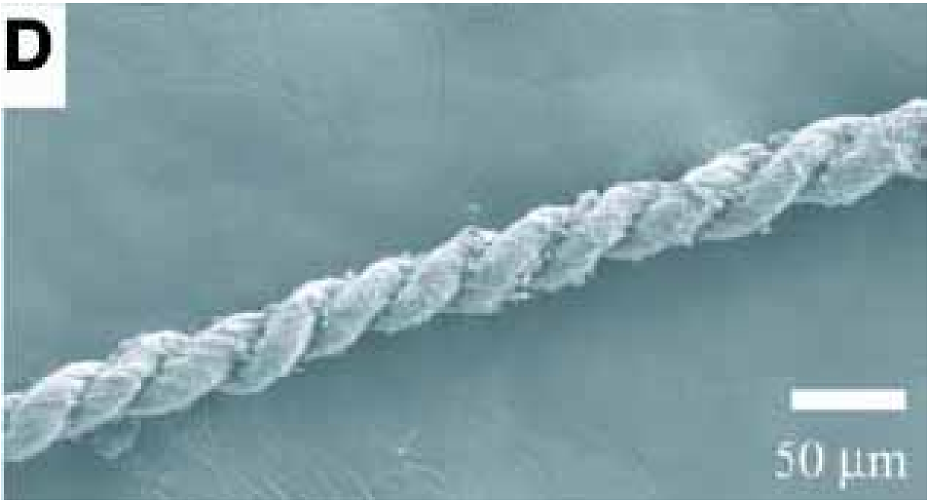


Carbon Nanotube Rope





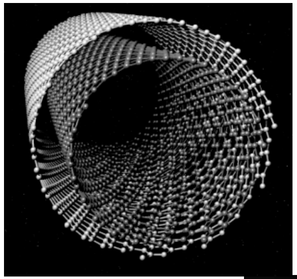


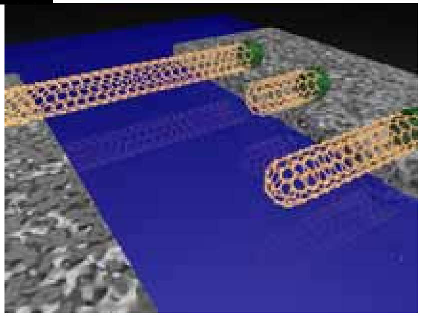


Lightbulbs with Carbon Nanotube Filaments

Lightbulbs with tungsten (left) or nano-wire (right) filaments.

結論





1) カーボンナノチューブの構造

2) カーボンナノチューブの成長とドーピング

3) トランジスタ応用

4) 一次元量子伝導

5) コヒーレント伝導

6) 単一電子伝導

7) その他