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Q-Machine Plasmas Yielding New Experimental Methodologies of Sheared-Flow and Nano-Quantum Physics.

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TOHOKU UNIVERSITY

Q-Machine Plasmas Yielding New Experimental Methodologies of Sheared-Flow and Nano-Quantum Physics

R. Hatakeyama and T. Kaneko

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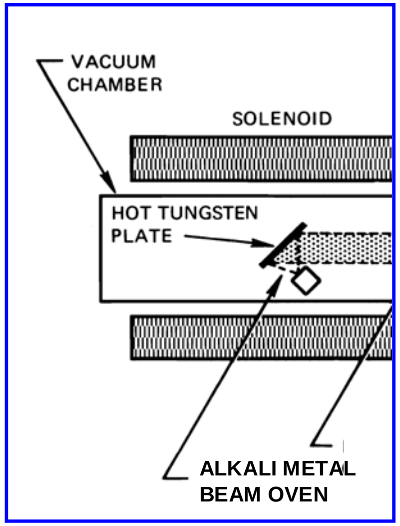
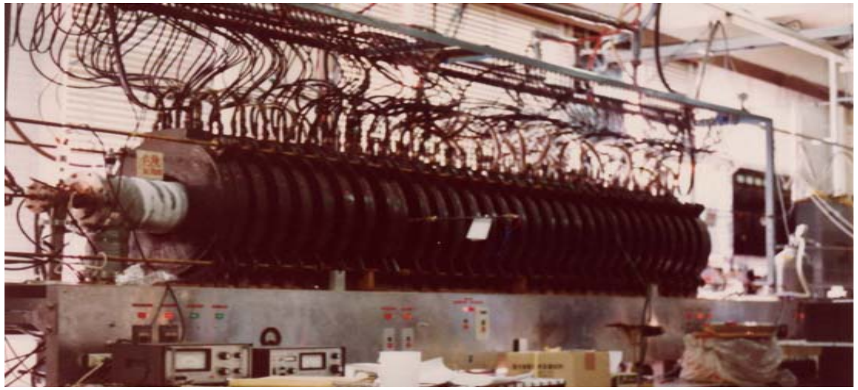
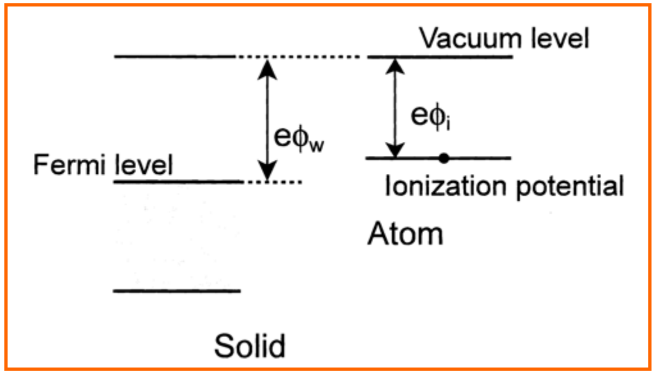




The Q machine has been used since the 1960s (~1958) : Ion acoustic, electron plasma, ion cyclotron, drift, … waves and instabilities, nonlinear phenomena such as double layers, …. in magnetized plasmas
⇒ Modification to sheared-flow physics study

Contact Ionization



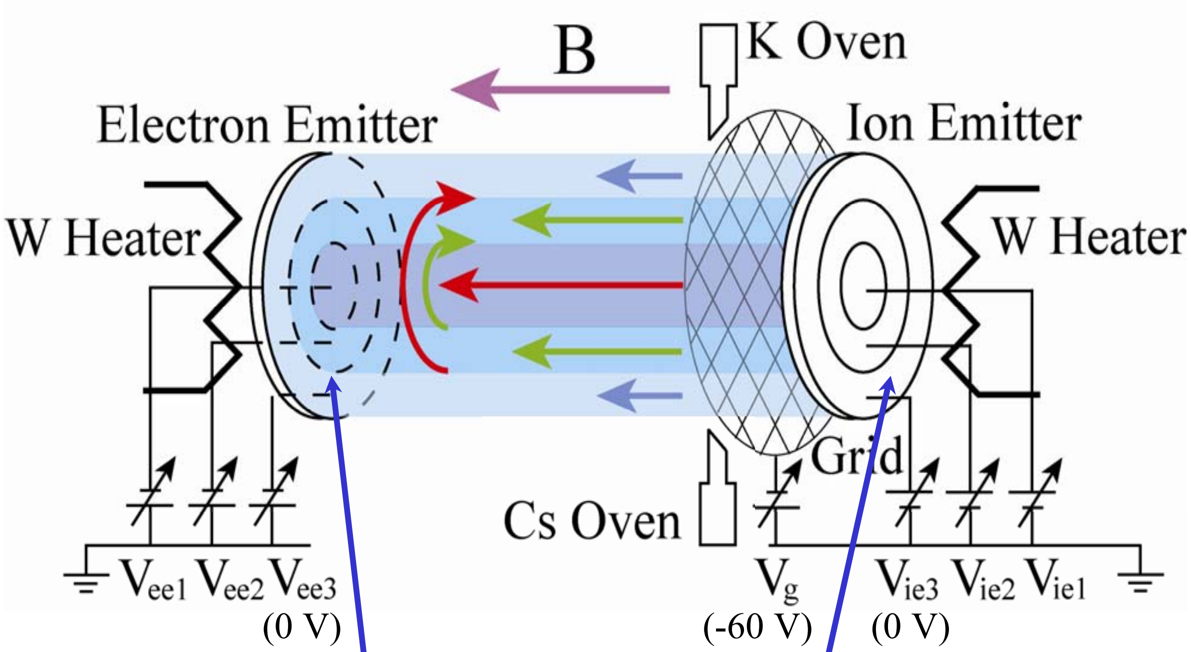
Work function of solid and ionization potential of atom.

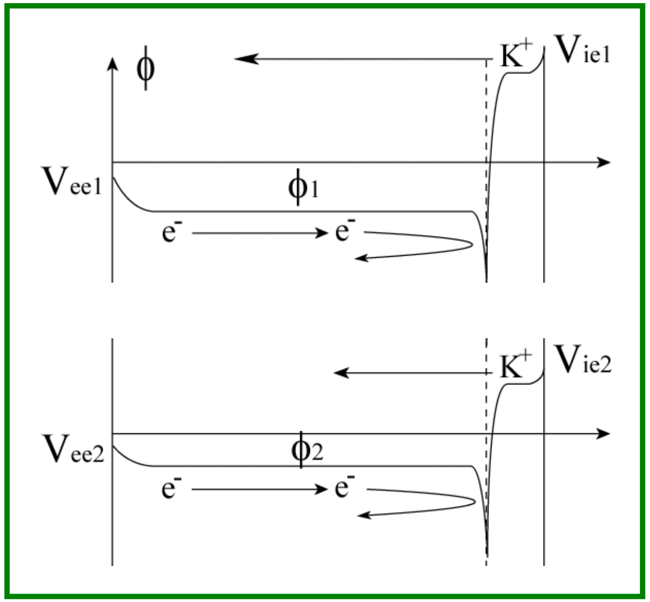
Innovative transformation of Q machines into the contribution to nano physics & chemistry fields since 1995.

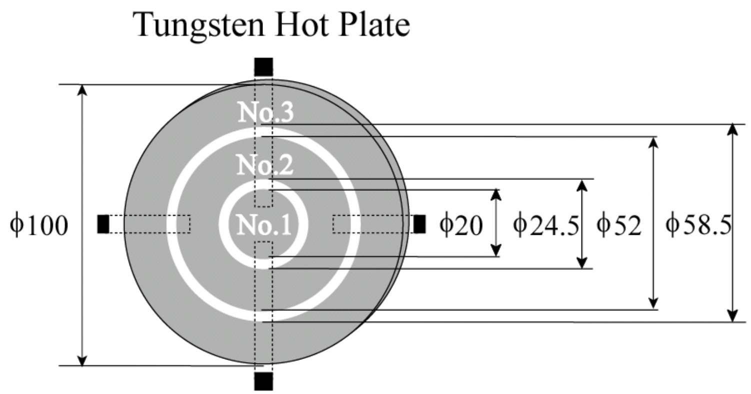
1. Q-Machine Modification Corresponding to Sheared-Flow Plasma Physics Study

Experimental Setup

Both the ion and electron emitters are concentrically segmented.

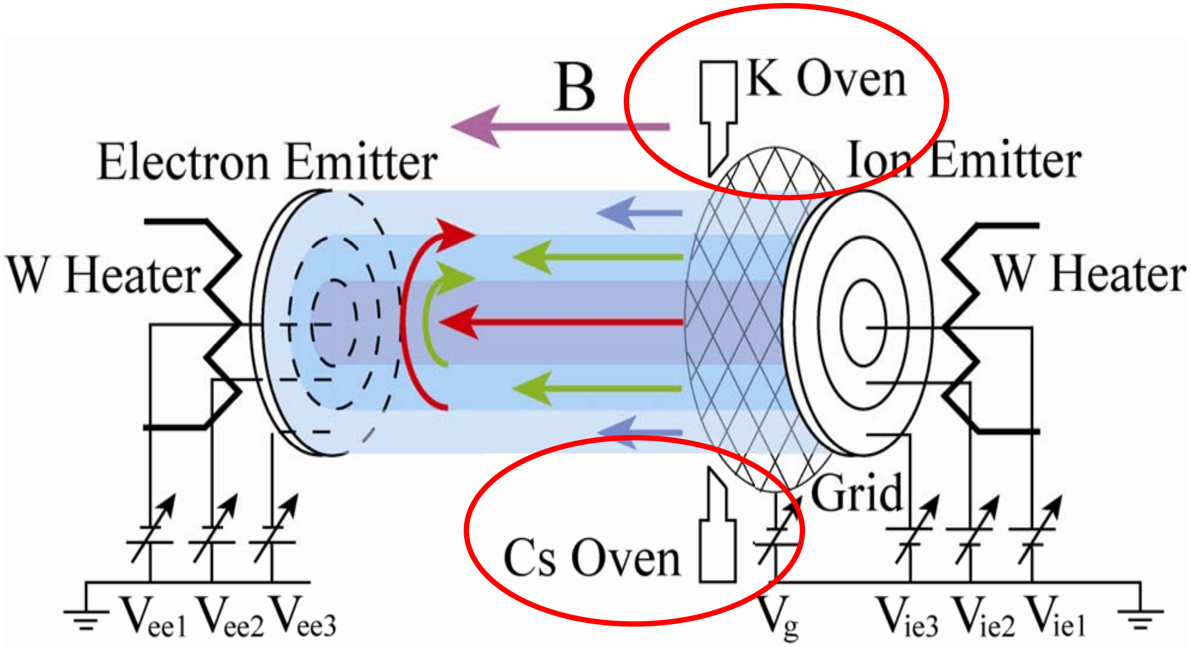


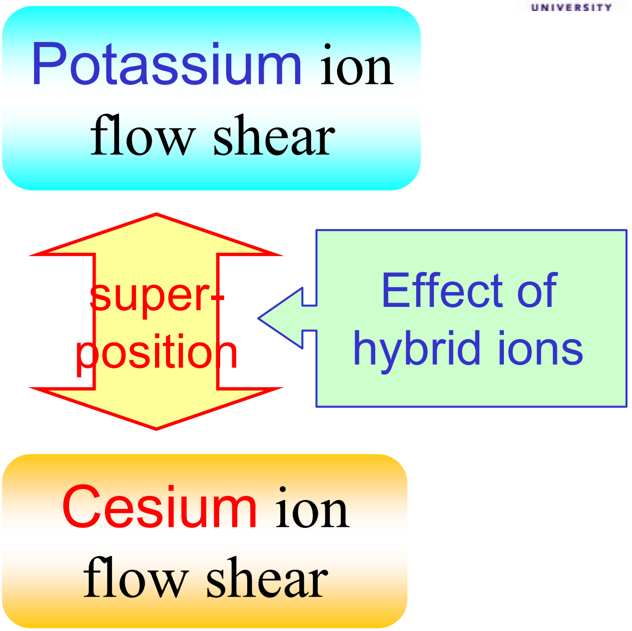




Rev. Sci. Instrum. **73** (2002) 4218

Superposition of $B_{||}$ and $B_{\perp}$ Flow Velocity Shears
Superposition of K and Cs Ion Flow Velocity Shears

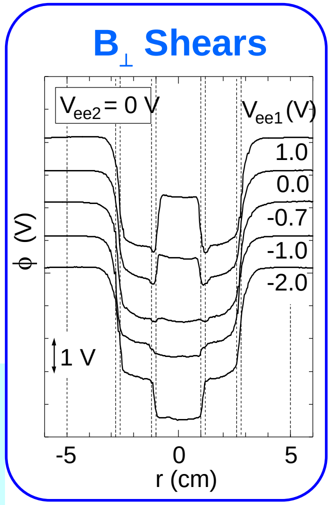


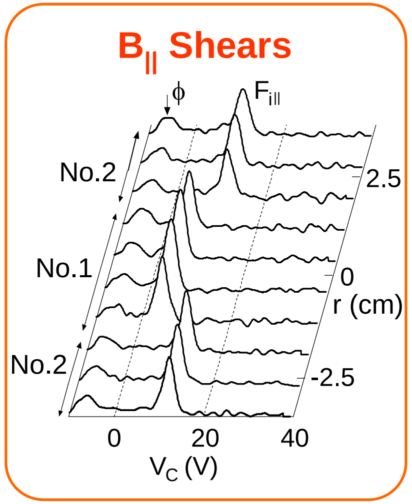


Electron Emitter
Determine space potential
⇒ E×B flow velocity
Control of perpendicular flow velocity shear

super-position

Ion Emitter
Determine ion flow energy parallel to B
Control of parallel flow velocity shear

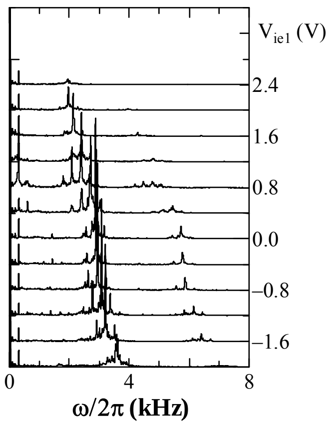




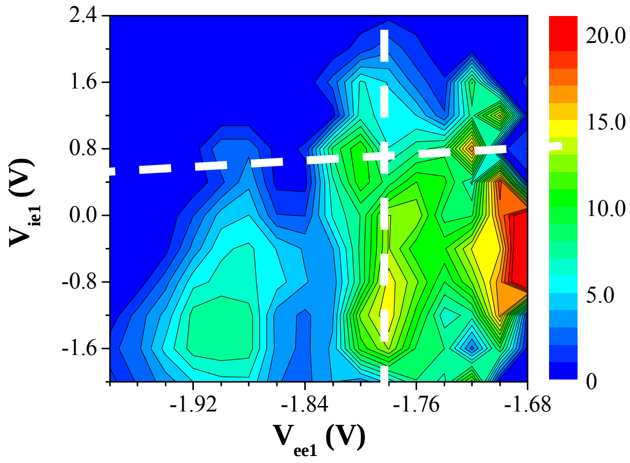
Phys. Rev. Lett. **90** (2003) 125001
Phys. Rev. Lett. **92** (2004) 069502
Phys. Plasmas **12** (2005) 072103
Phys. Plasmas **12** (2005) 102106
Phys. Scripta **T107** (2004) 200
Trans. Fusion Sci. Technol. **47** (2005) 128
Trans. Fusion Sci. Technol. **51** (2007) 103
Plasma Fusion Res. **3** (2008) S1011

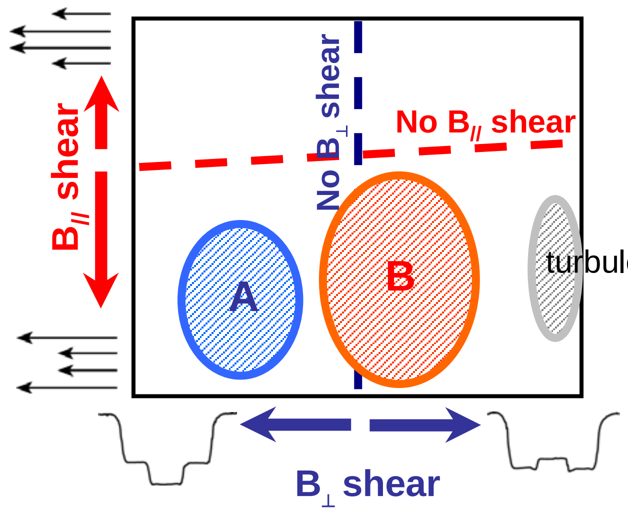
Superposition of $B_{\parallel}$ and $B_{\perp}$ Flow Velocity Shears (Drift Wave)

V_{ie2}= 1.0 V , V_{ee2}= -2.00 V

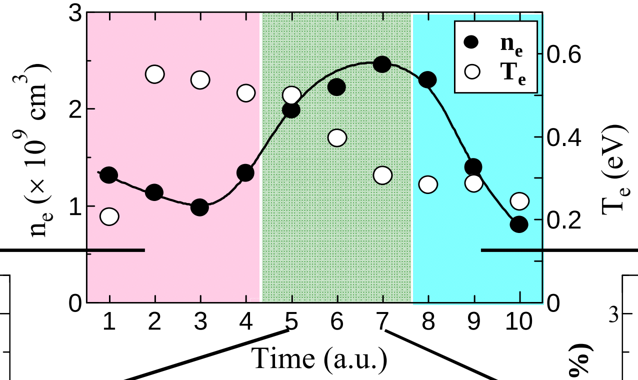


Normalized fluctuation amplitude at r = -1.0 cm (shear region).



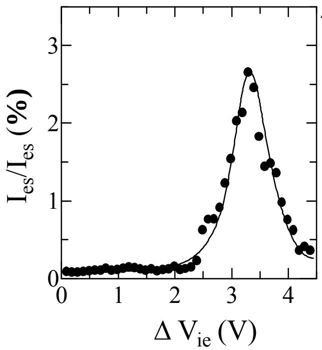


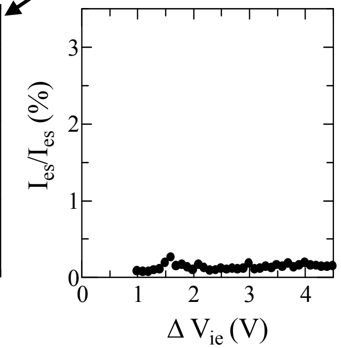
Superposition of K and Cs Ion Flow Velocity Shears (Drift Wave)



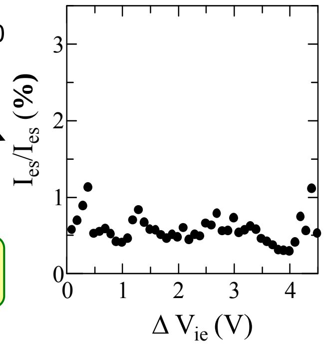
Cs

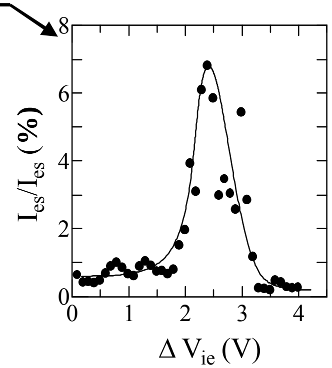
K





Cs + K





Electron Temperature Gradient Instabilities in Magnetized Plasmas

INTRODUCTION

TOHOKU UNIVERSITY

Temperature Gradient Driven Modes in Magnetically Confined Plasmas

Ion Temperature Gradient (ITG) Modes

- **ITG modes are the most plausible candidate for the anomaly of ion channel thermal transport.**
- **EXB sheared flow suppression effects on ITG modes are identified[1,2].**

Electron Temperature Gradient (ETG) Modes

- **ETG modes are also the plausible candidate for the electron transport properties of tokamak devices [3].**
- **ETG modes are difficult to be stabilized by EXB shear.**

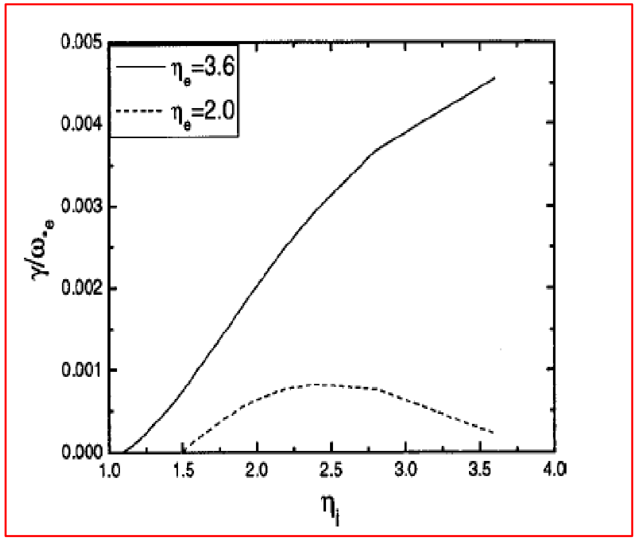
[1] Z. Gao, H. Sanuki , K. Itoh, and J.Q. Dong, Phys. Plasmas **10** (2003) 2831.
[2] Z. Gao, J. Q. Dong, and H.Sanuki, Phys. Plasmas **11** (2004) 3053.
[3] Y.C. Lee, J. Q. Dong, P.N. Guzdar, and C.S. Liu, Phys. Fluids **30** (1987) 1331.

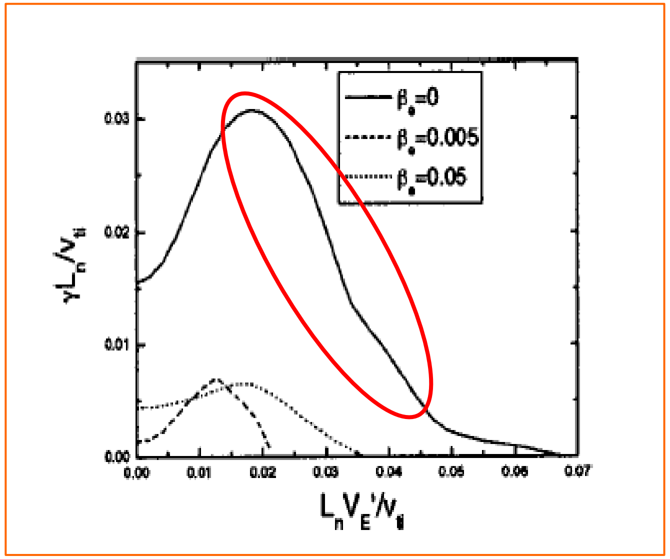
Why ETG Mode is Important?

- Experimental observation expresses that the low frequency instability is driven by ETG and nonlinear effects of ETG modes generate significant electron transport.
- The growth rate of ETG mode is about 20 times larger than that of short wave length ITG mode.
- It is an important issue to reduce the electron thermal transport observed in magnetically confined fusion devices.
- Therefore it is necessary to examine the role of ETG driven mode in a linear machine so that the result would be applicable in tokamak plasmas.

Stabilization by ExB shear

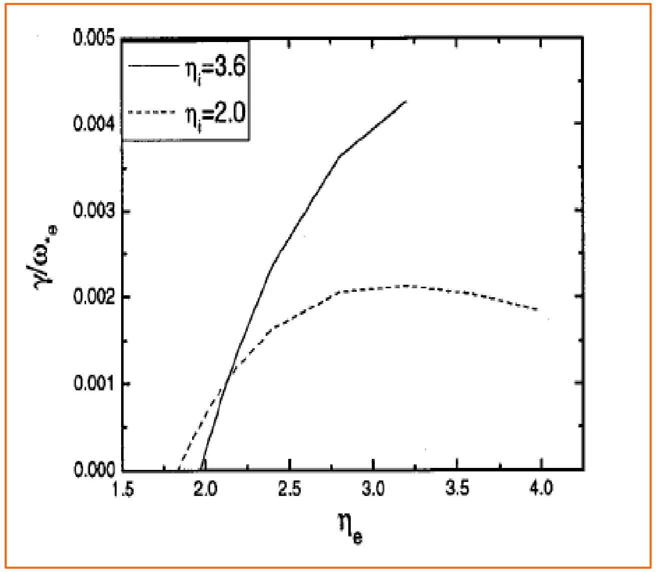
ITG mode

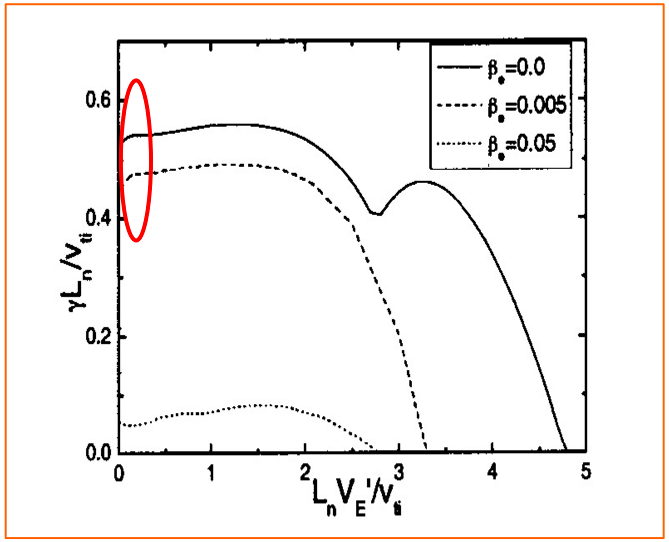




Where, $\eta_{e,i} = \dfrac{d\ln T_{e,i}}{d\ln n_{e,i}}$ **= electron, ion temperature gradient, and V_E' is the EXB shear velocity.**

ETG mode





Theoretically investigated by Z. Gao, et al., Phys. Plasmas **10** (2003) 2831, **11** (2004) 3053.

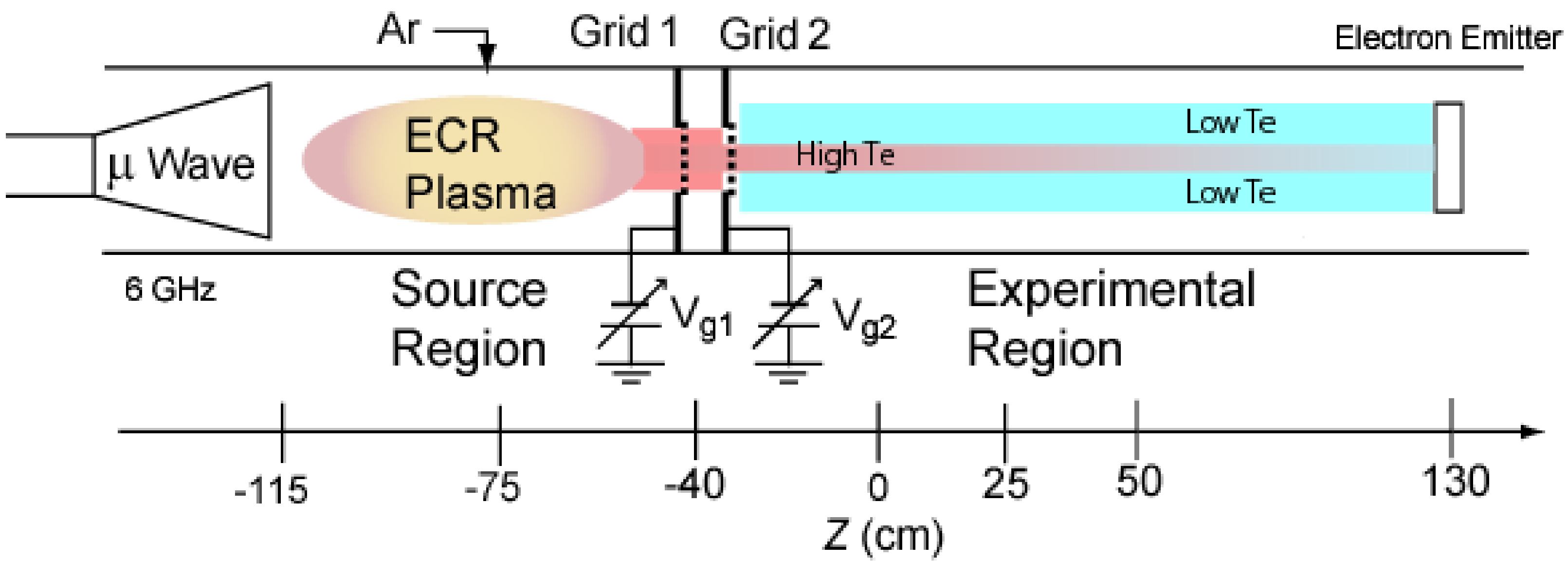
- **In laboratory experiments, several techniques have been applied to the control of the electron temperature[4-6], but it is difficult to realize spatially different electron temperatures at a localized area.**

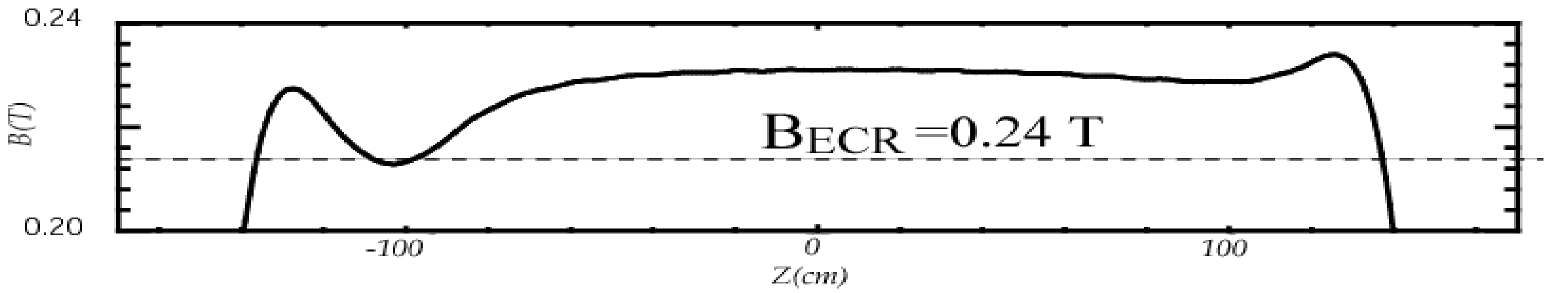
Objective

To produce and control electron temperature gradient (ETG) using a thermionic electron superimposed electron cyclotron resonance (ECR) plasma and applying voltages to two different sized mesh grids and finally to examine the stabilization of ETG mode by E X B sheared suppression in a linear machine..

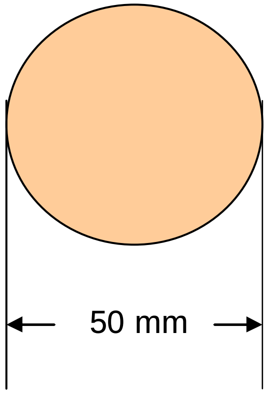
[4] G. T. Hoang, et al. Phys. Rev. Lett. **87** (2001) 125001.
[5] F. Porcelli, E. Rossi, G. Cima, and A Wootton , Phys. Rev. Lett. **82** (1999) 1458.
[6] K. Kato, S. Iizuka, and N. Sato, Appl. Phys. Lett. **65** (1994) 816.

EXPERIMENTAL APPARATUS

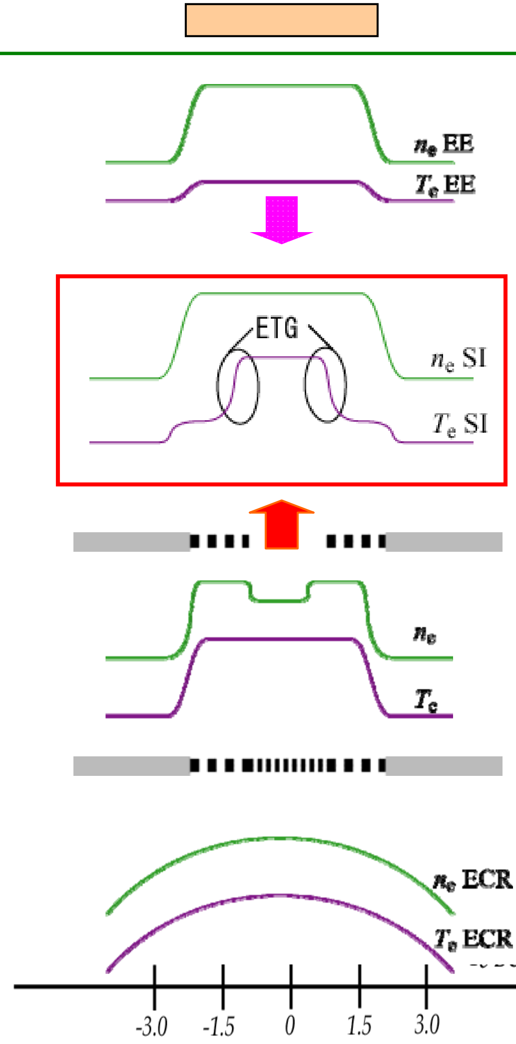




Electron emitter (W hot plate)



Electron emitter (W hot plate)



Supply of thermionic low T_e electrons from electron emitter (EE)

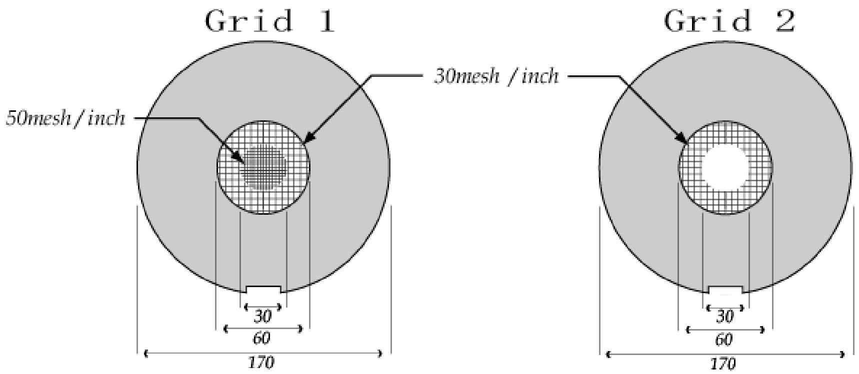
Thermionic electrons superimposed (SI) ECR plasma

Grid 2

Grid 1

High T_e electrons in ECR plasma

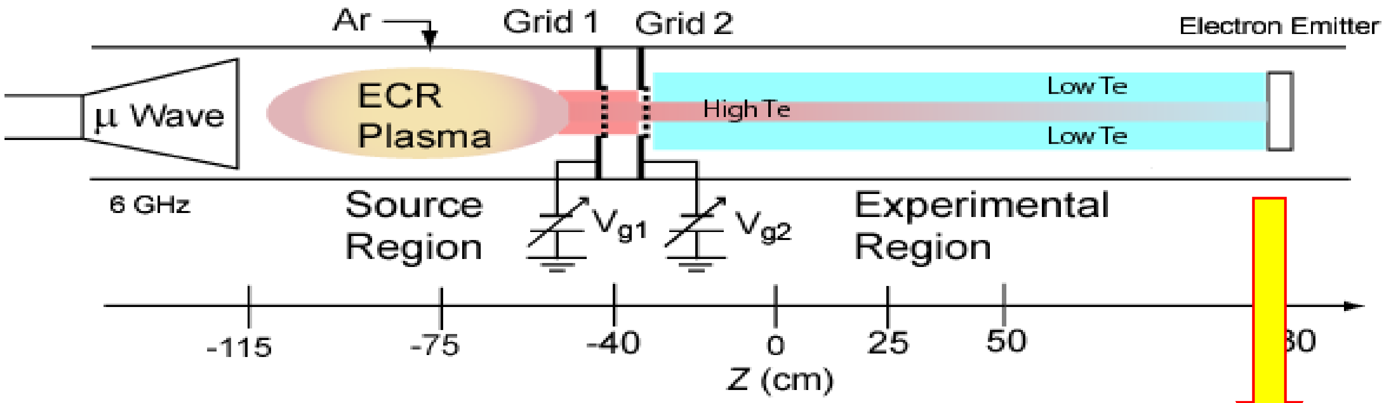
Construction of mesh grids

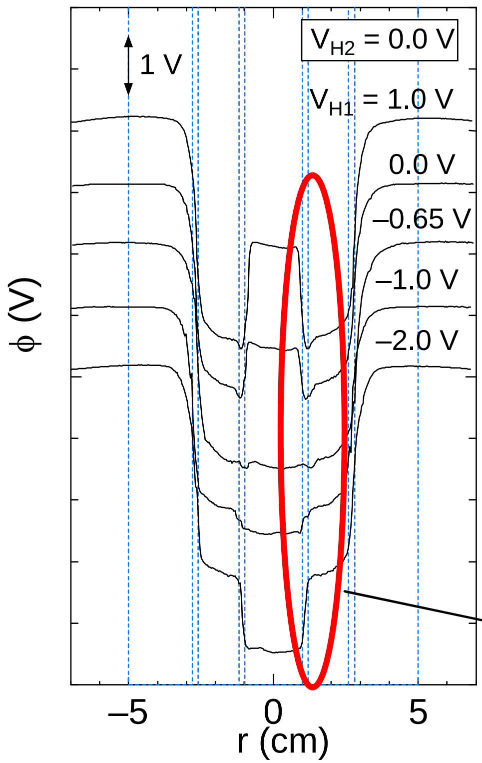


Grid bias: additional discharge generates low T_e electron

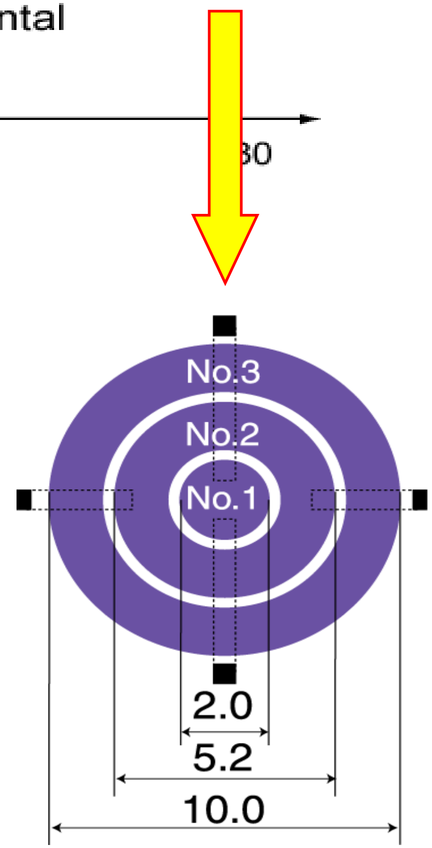
Deformation of density and temperature profiles from source to experimental region due to mesh grids

EXB sheared suppression





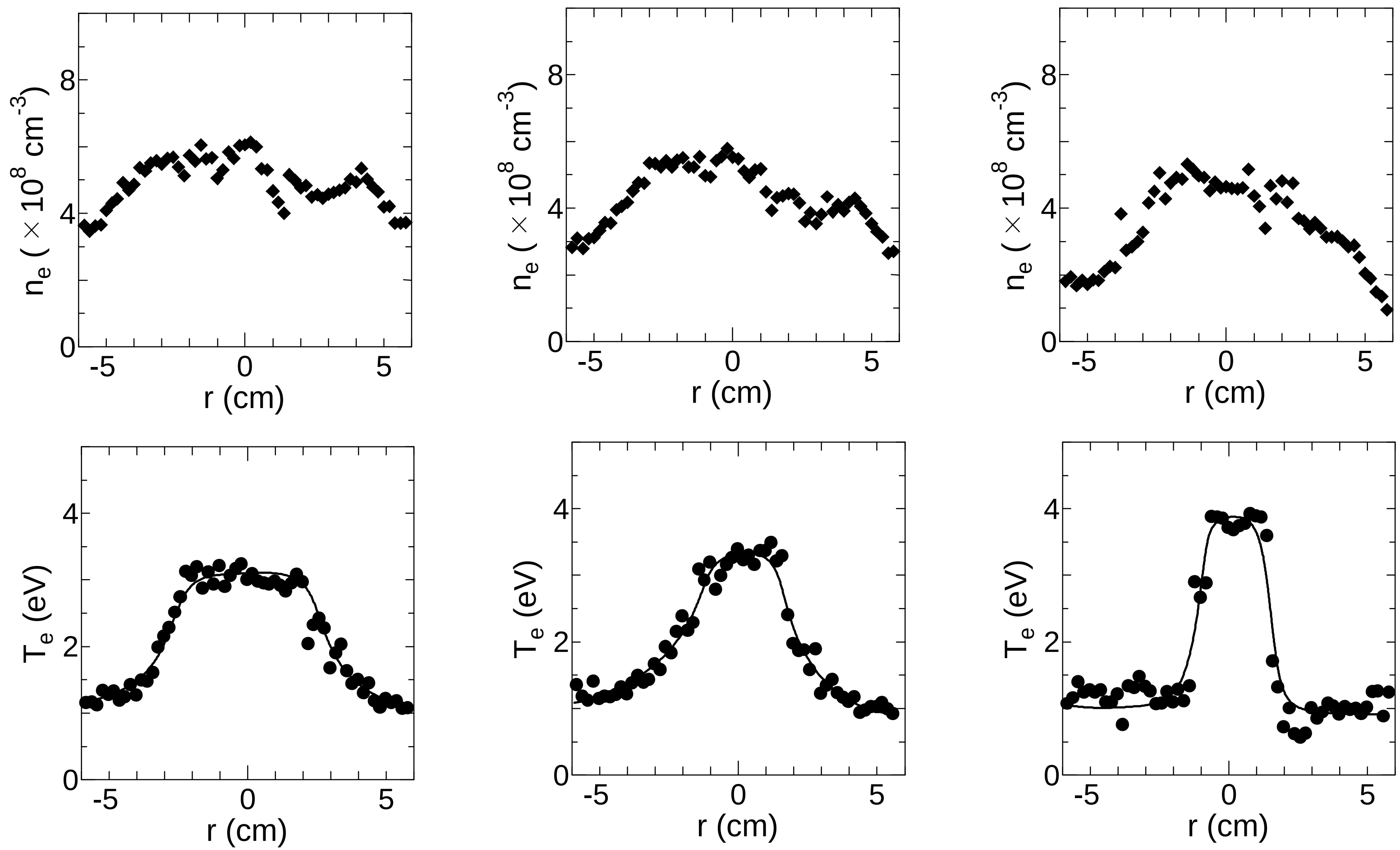
By applying different voltages to the electrodes 1, 2, and 3, radial profiles of plasma potentials can be changed and as a result E X B shear is generated in the central region



E X B shear is generated

Formation and Control of ETG in thermionic electron superimposed ECR plasmas by changing v_{g2}

v_{g1}= floating potential



v_{g2}=-5V

v_{g2}= -10V

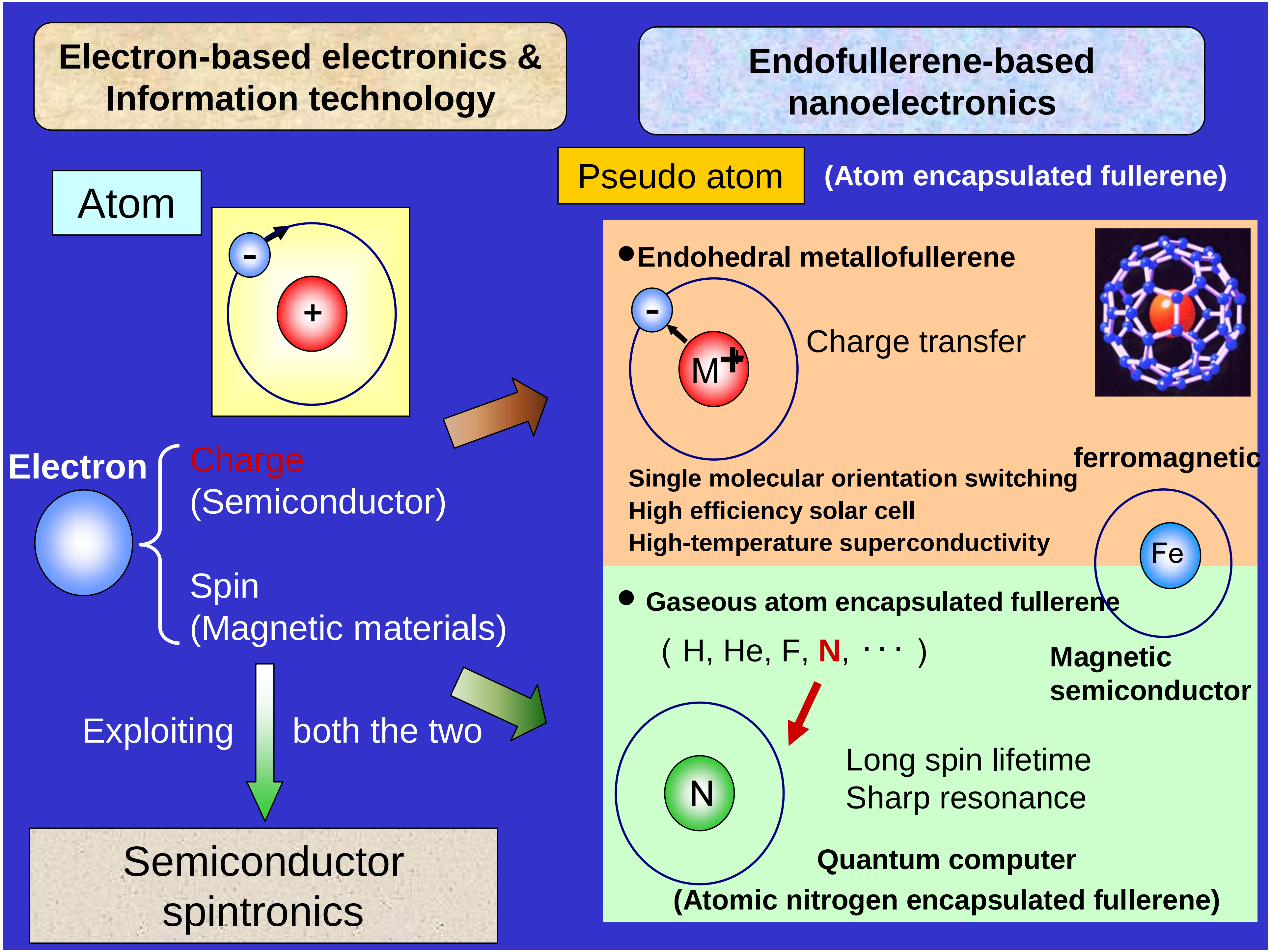
v_{g2}=-50V

No ETG is formed

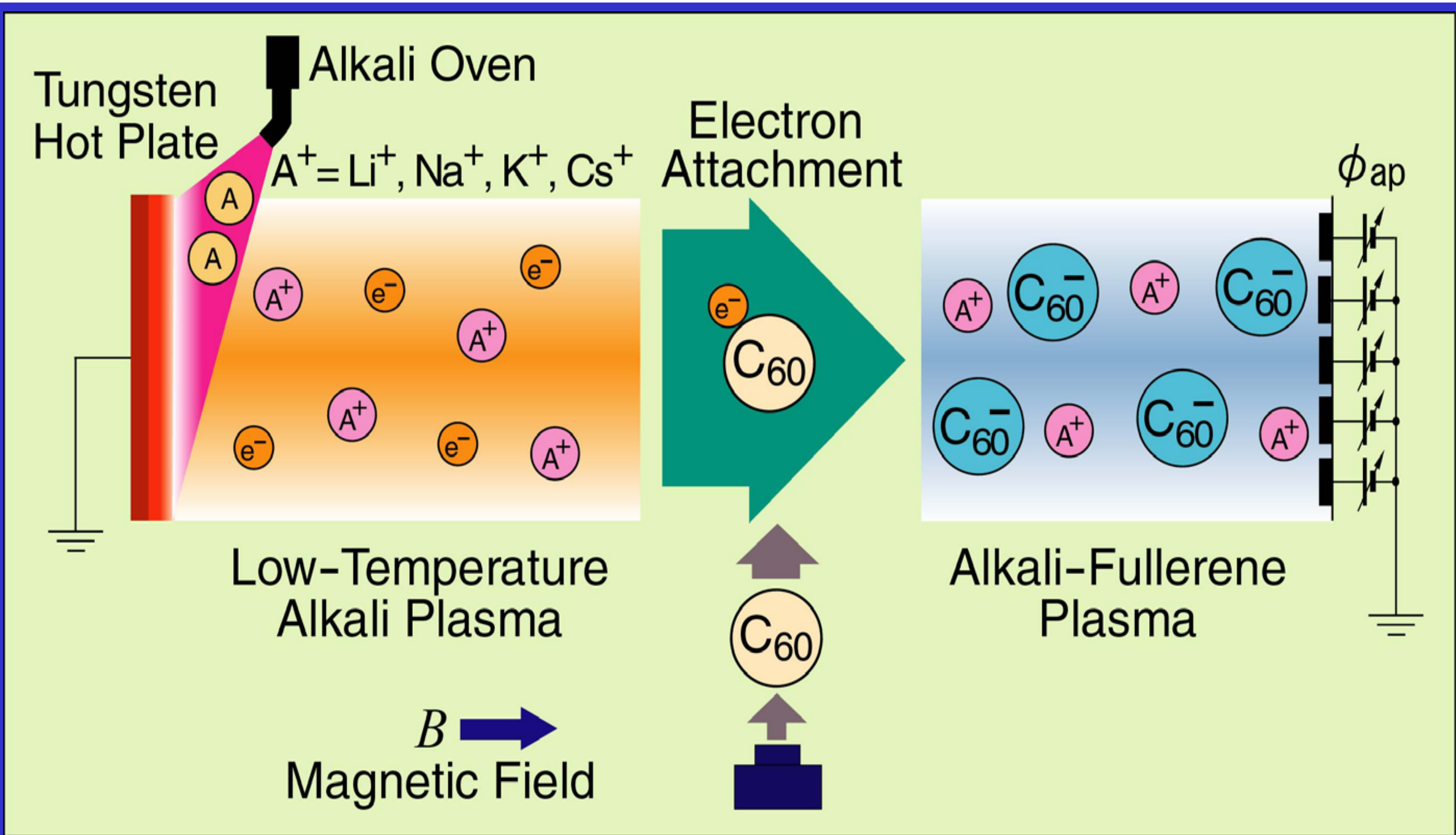
Small ETG is formed

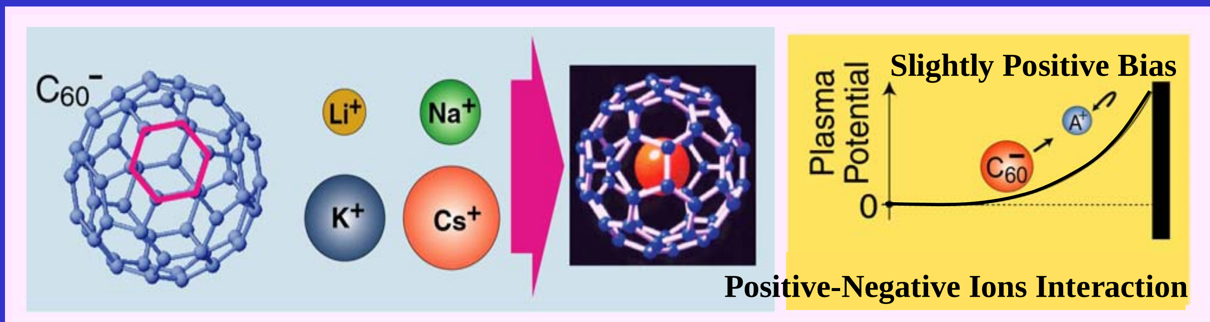
ETG becomes large

2. Innovative Transformation of Q Machine Corresponding to Nano Physics & Chemistry Study


Electron-based electronics & Information technology
Endofullerene-based nanoelectronics
Pseudo atom
(Atom encapsulated fullerene)
Atom
-
+
Electron
Charge
(Semiconductor)
Spin
(Magnetic materials)
Exploiting
both the two
Semiconductor spintronics
Endohedral metallofullerene
-
M+
Charge transfer
ferromagnetic
Single molecular orientation switching
High efficiency solar cell
High-temperature superconductivity
Fe
Gaseous atom encapsulated fullerene
(H, He, F, N, · · ·)
Magnetic semiconductor
N
Long spin lifetime
Sharp resonance
Quantum computer
(Atomic nitrogen encapsulated fullerene)

Generation of Alkali-Fullerene Plasma

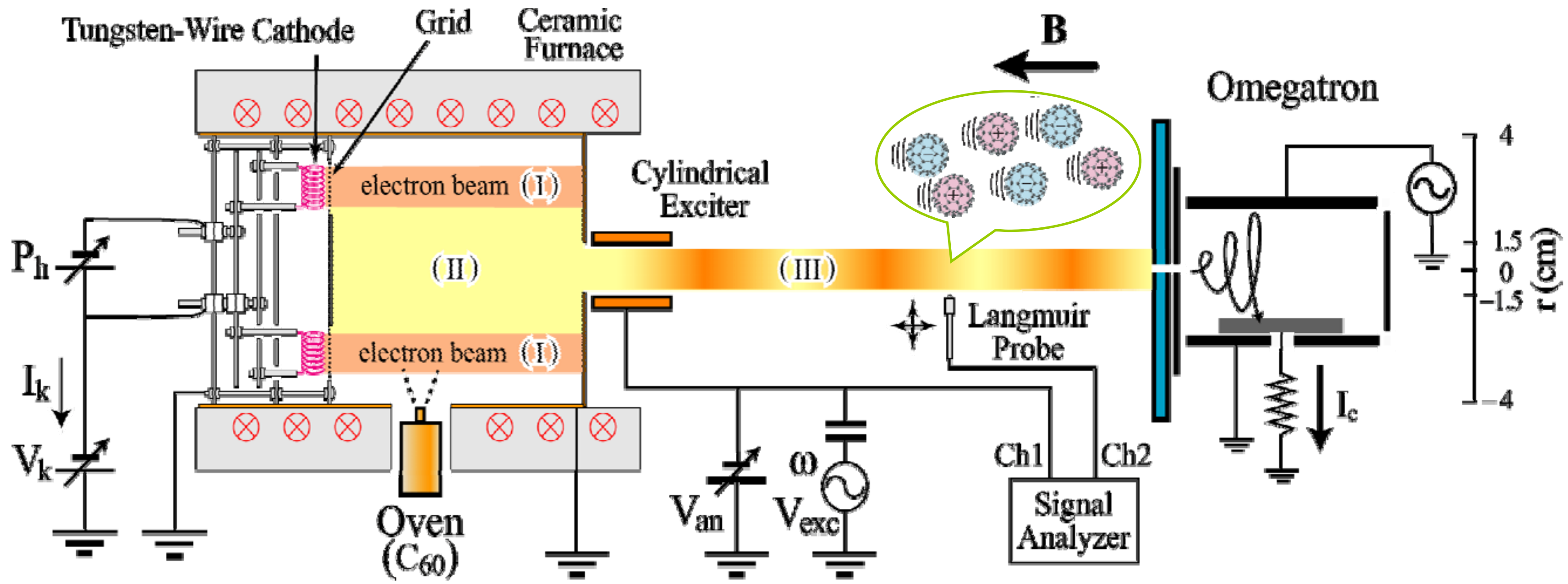


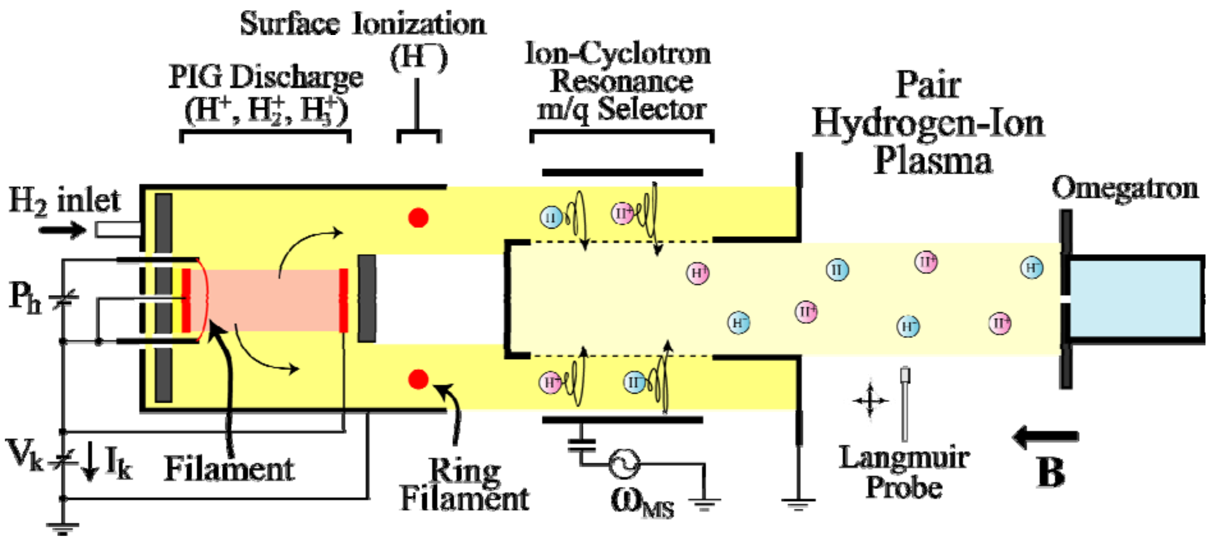


Phys. Plasmas **1** (1994) 3480

J. Vac. Sci. Technol. **A 14** (1996) 615

Pair C_{60}-Ion and H-ion Plasmas





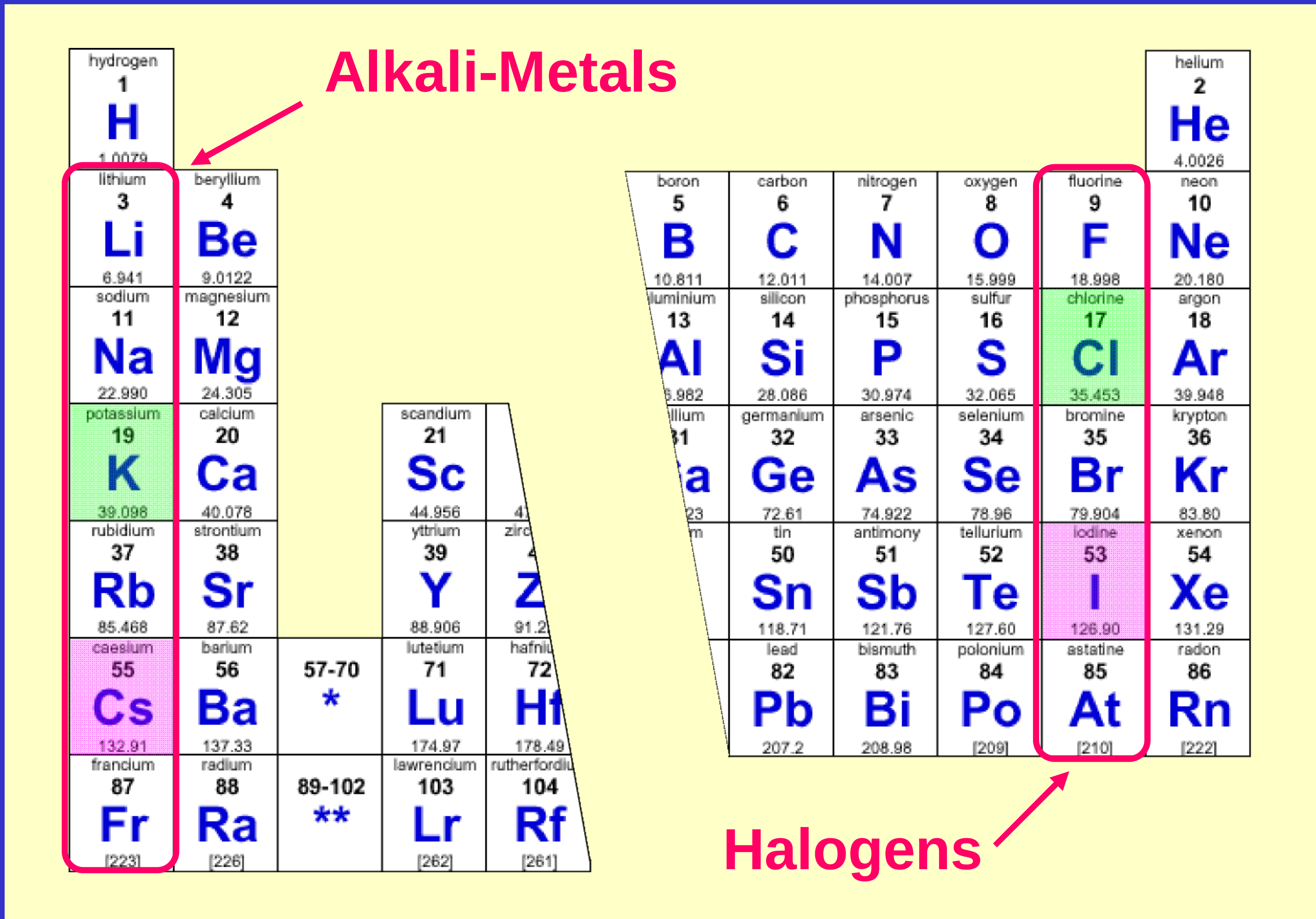
Phys. Rev. Lett. **91** (2003) 205005

Phys. Rev. Lett., **95** (2005) 175003

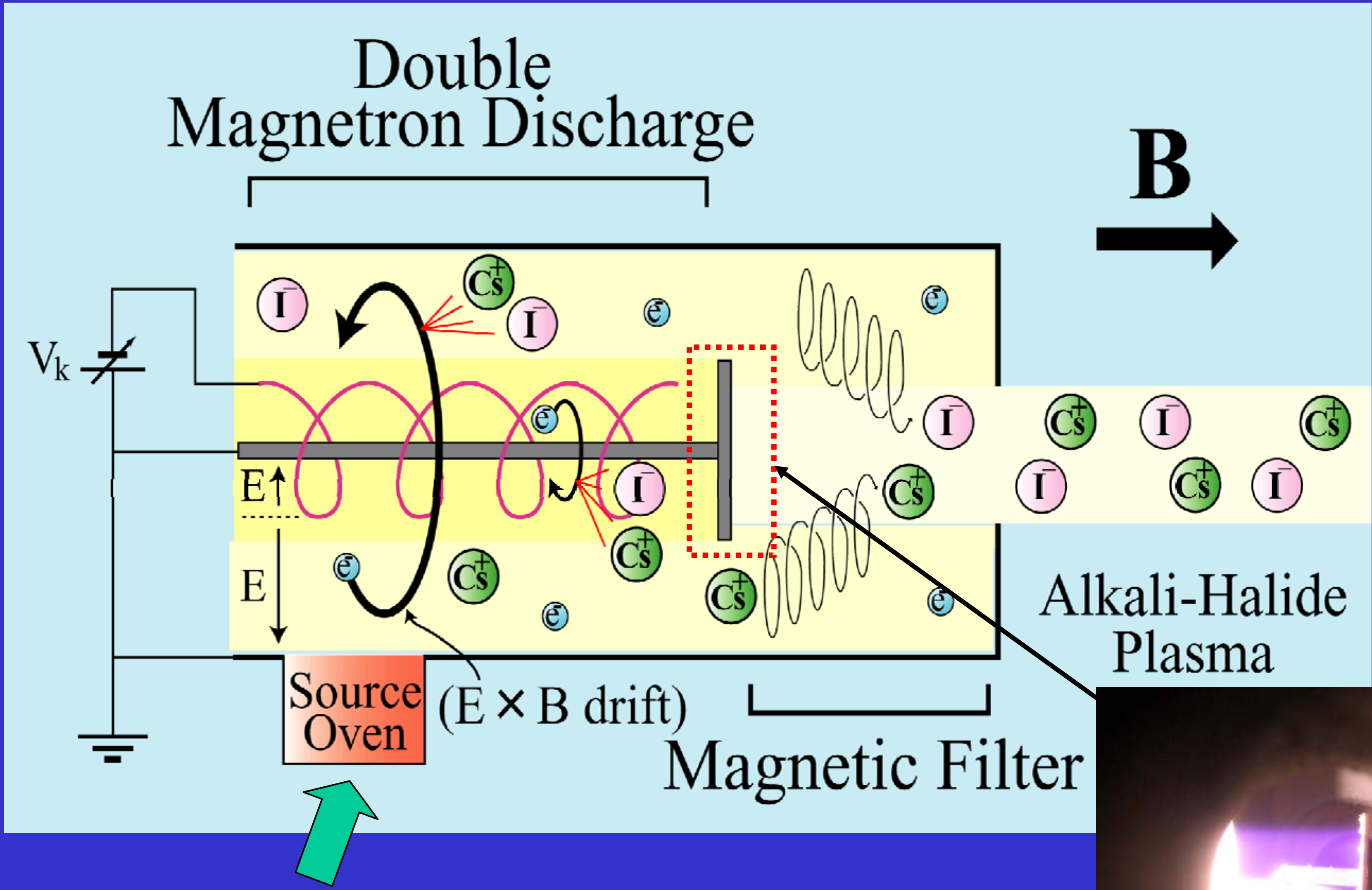
Phys. Rev. E, **75** (2007) 056403

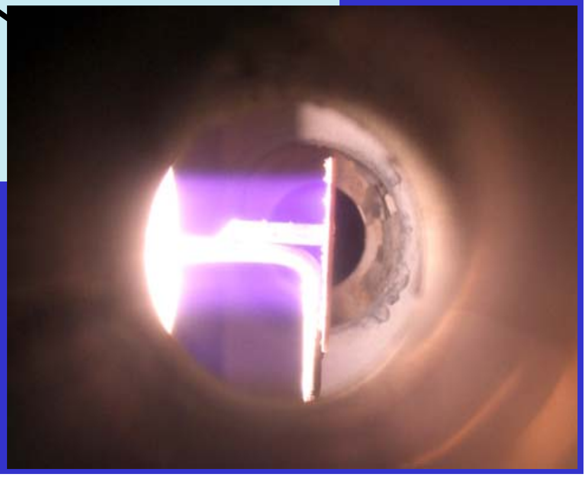
Phys. Plasmas, **14** (2007) 055704

Periodic Table



Alkali-Halogen ($Cs^+ – I^-$) Plasma Generation

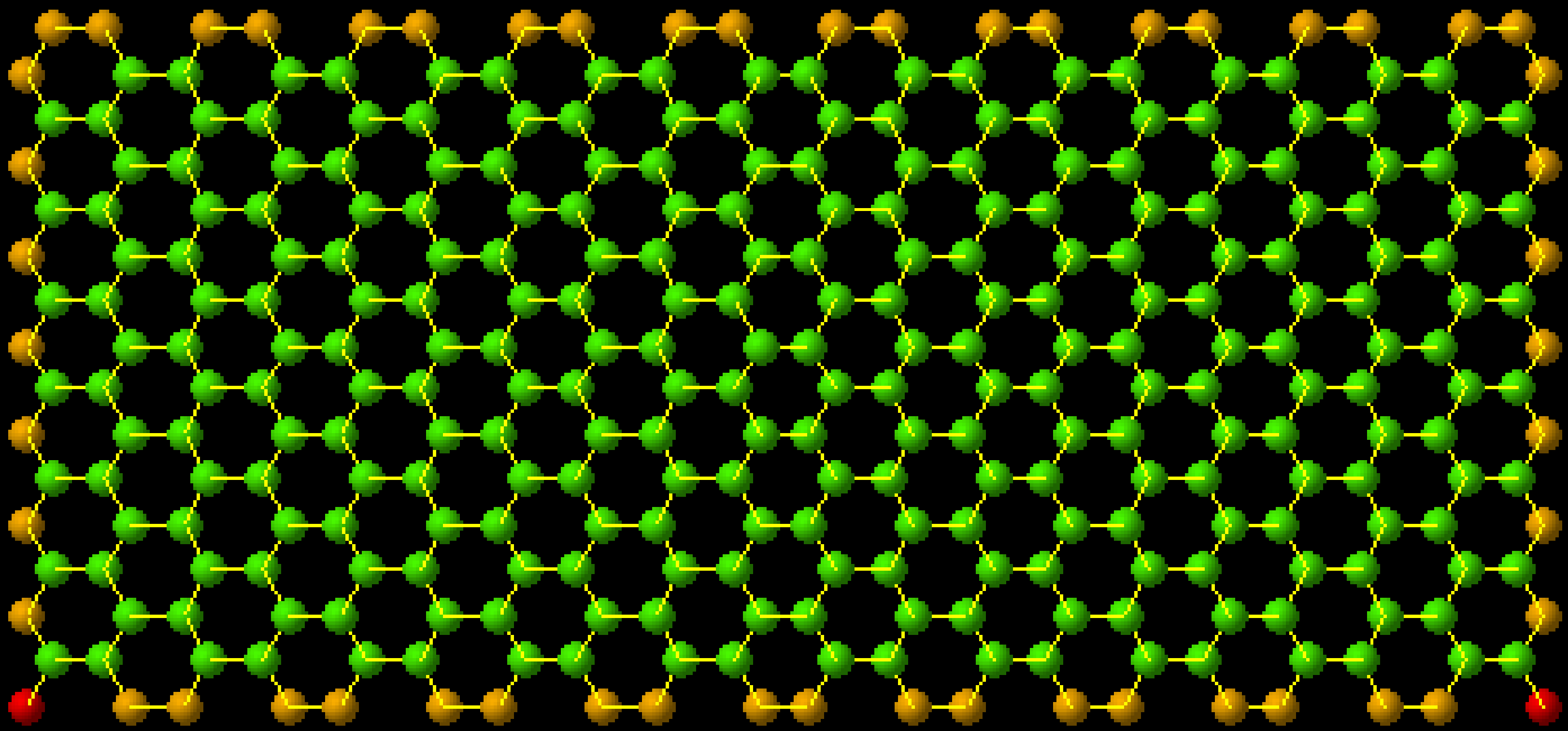




Salt: KCl, CsCl, CsI,

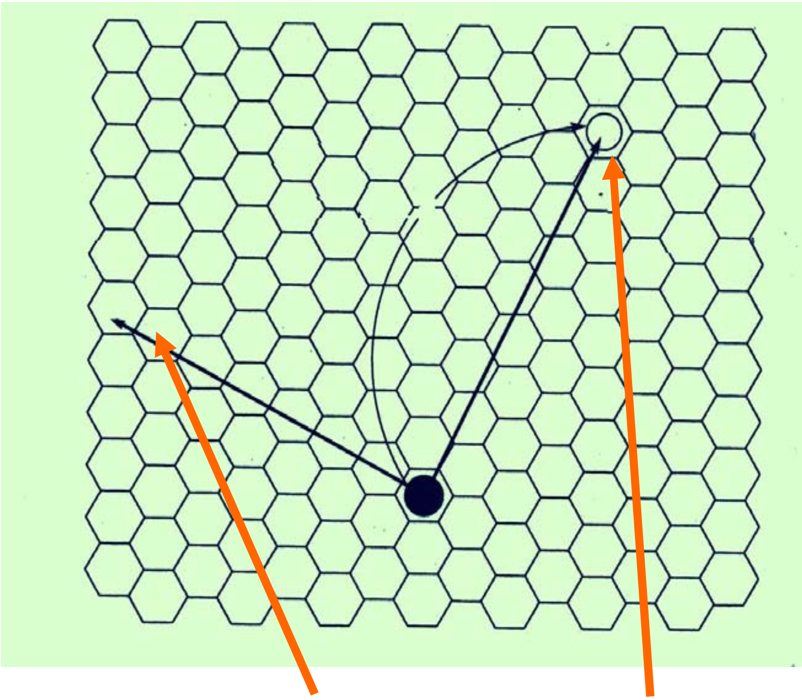
. Appl. Phys. Lett. **88** (2006) 191501

(10,10)

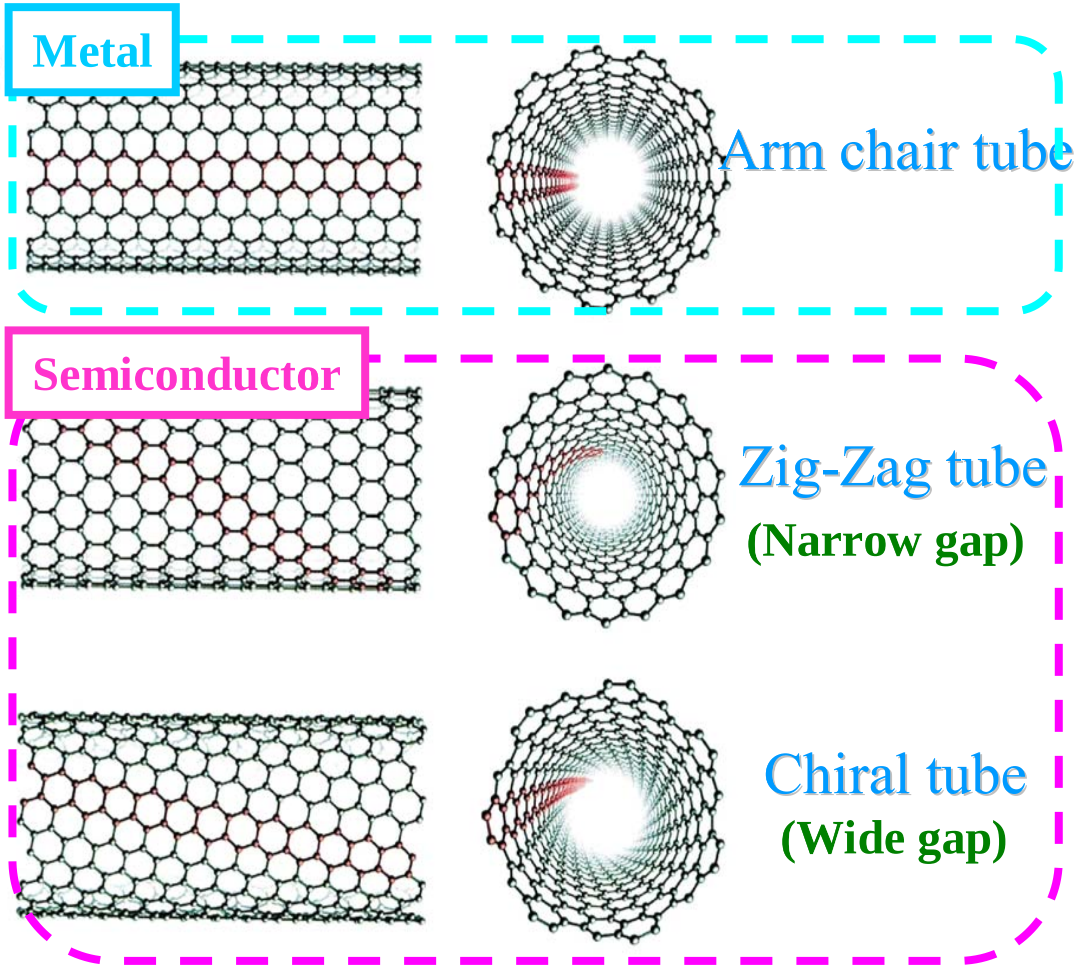


From the home page of Maruyama Lab, Univ. Tokyo
http://www.photon.t.u-tokyo.ac.jp/index-j.html

Carbon Nanotube Properties



Translation vector Chiral vector



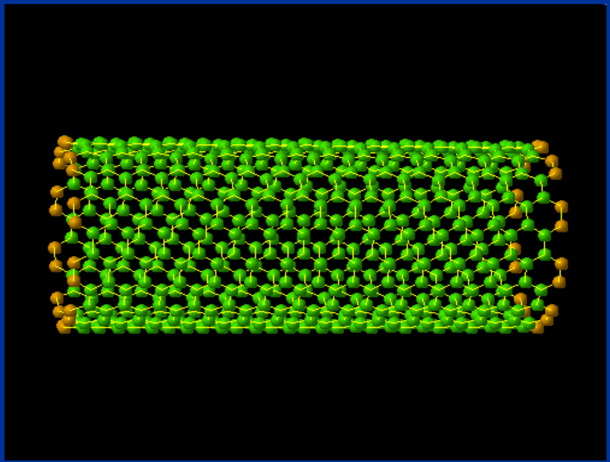
Tube electric properties drastically change from metal to semiconductor

by slight differences of their structure (without any impurity doping)

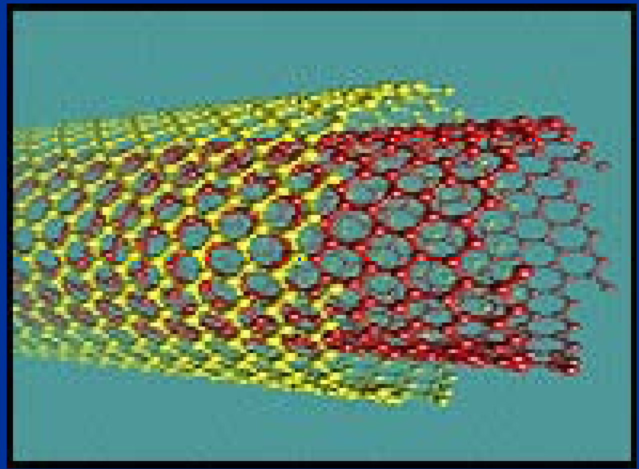
Creation of Evolved Carbon Nanotubes

There are 3 basic types of nanotubes

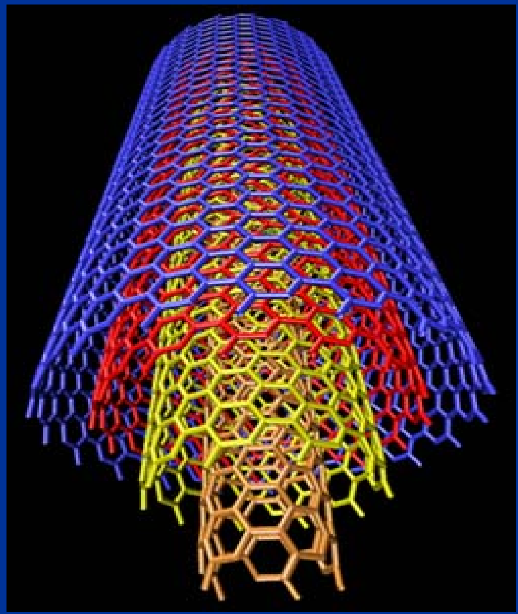
Diameter: ~ nm
Length: < nm ~ μm ~ mm



SWNT: single-walled nanotube

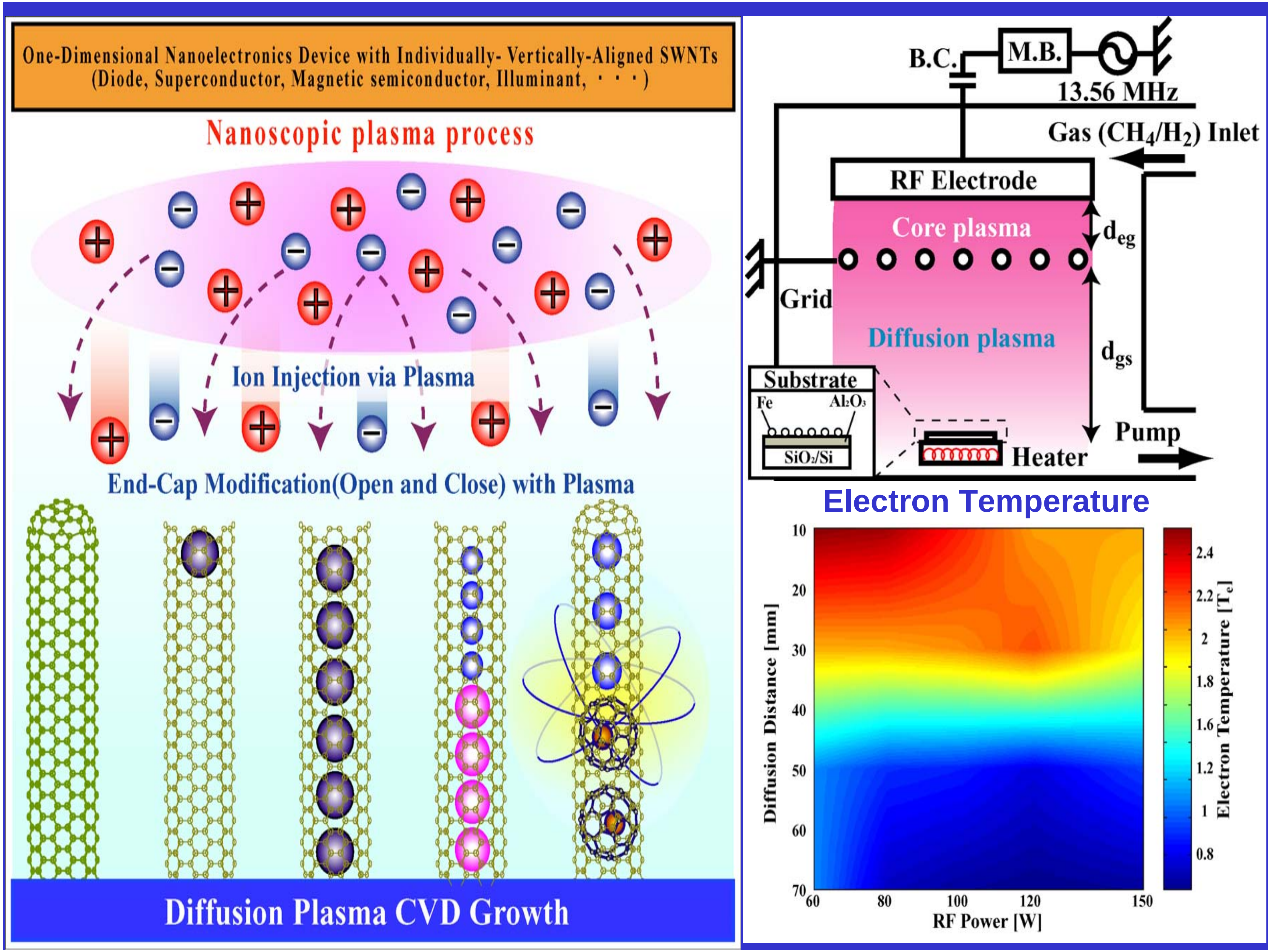


DWNT: double-walled nanotube



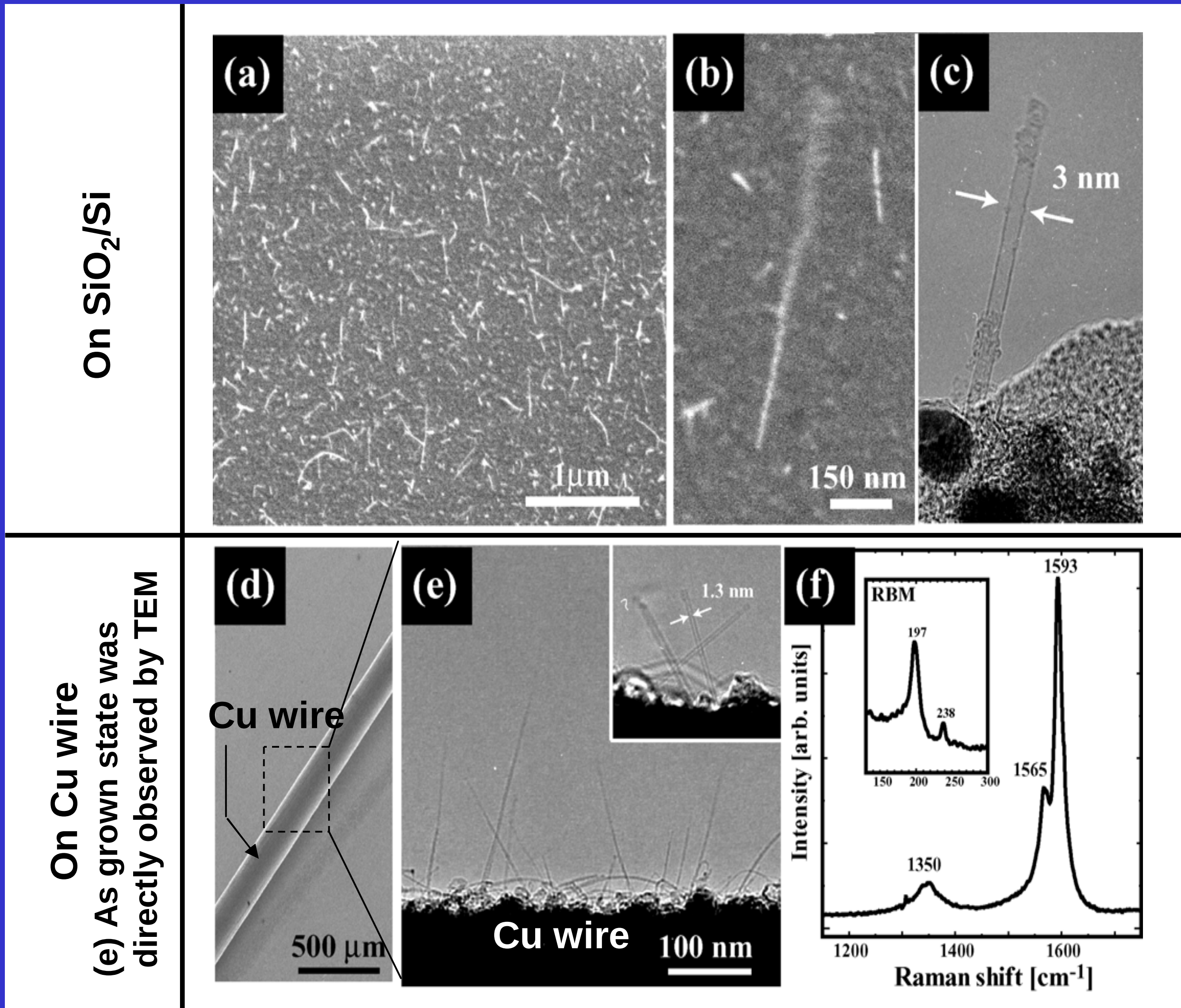
MWNT: multi-walled nanotube

Appl. Phys. Lett. **83** (2003) 119
J. Appl. Phys. **96** (2004) 6053



One-Dimensional Nanoelectronics Device with Individually- Vertically-Aligned SWNTs
(Diode, Superconductor, Magnetic semiconductor, Illuminant, · · ·)
Nanoscopic plasma process
Ion Injection via Plasma
End-Cap Modification(Open and Close) with Plasma
Diffusion Plasma CVD Growth
B.C.
M.B.
13.56 MHz
Gas (CH_4/H_2) Inlet
RF Electrode
Core plasma
d_{eg}
Grid
Diffusion plasma
d_{gs}
Substrate
Fe
Al_2O_3
SiO_2/Si
Heater
Pump
Electron Temperature
Diffusion Distance [mm]
RF Power [W]
Electron Temperature [T_e]

Freestanding growth of individual SWNTs on a flat substrate



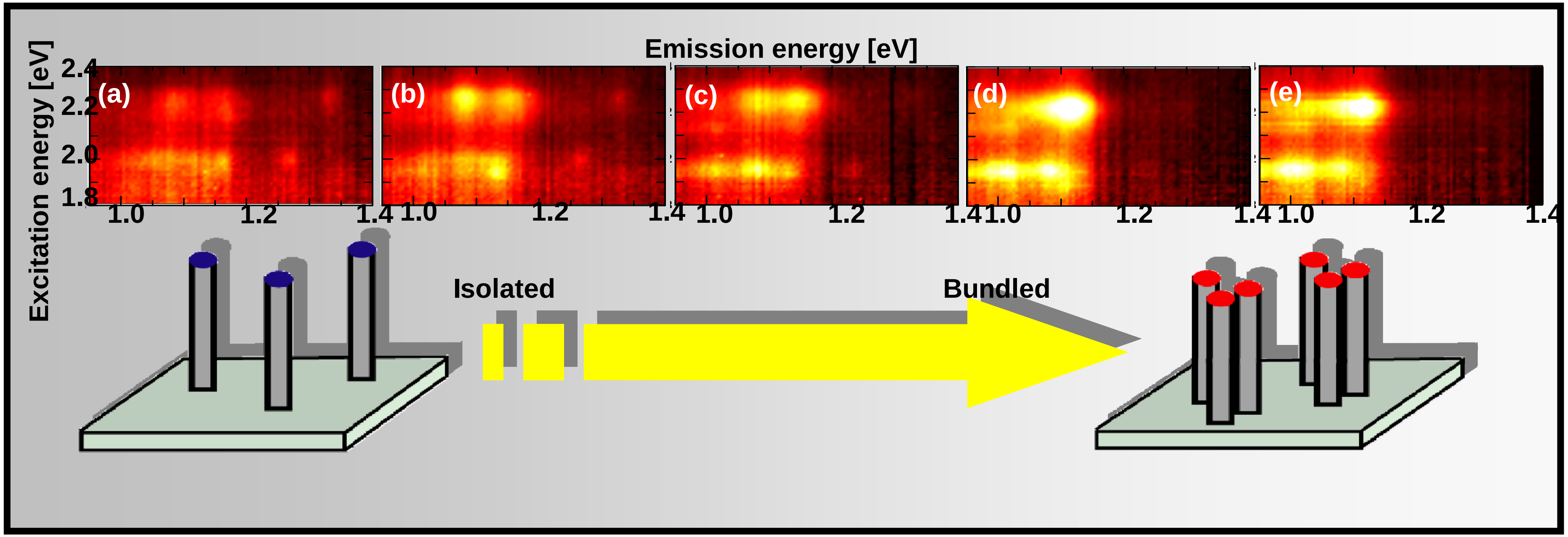
- Dgs : 20, 70 mm,
- P_{RF} : 40 W,
- T_{pro} : 60, 180 sec,
- T_{sub}: 700, 750℃

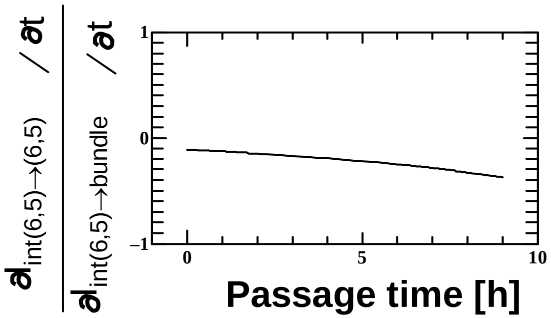
From these results (SEM, TEM, Raman)

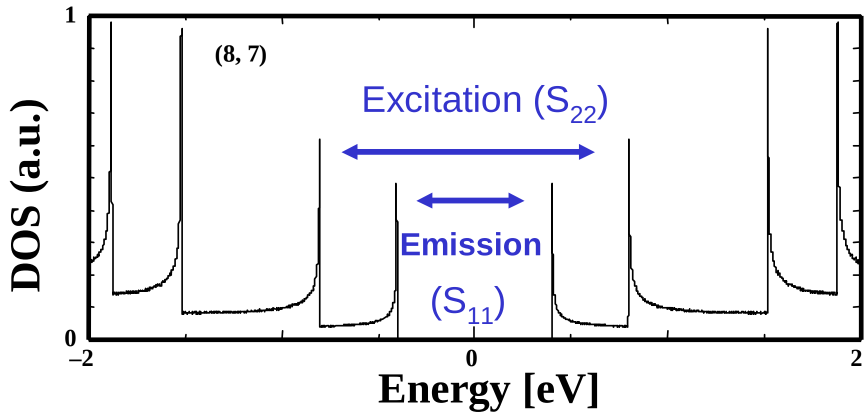
Freestanding-individual SWNTs have been successfully produced on a silicon-based flat substrate due to plasma-sheath effect !!

Chem. Phys. Lett. **381** (2003) 422; *Jap. J. Appl. Phys. (Exp. Lett.)* **43** (2004) L1278; *Nanotechnol.* **17** (2006) 2223 ; *Appl. Phys. Lett.* **92** (2008) 031502

Unique photoluminescence features in freestanding SWNTs







$$\frac{\partial S(t)_{(6,5)}}{\partial t} + \frac{\partial S(t)_{bundle}}{\partial t} = 0$$

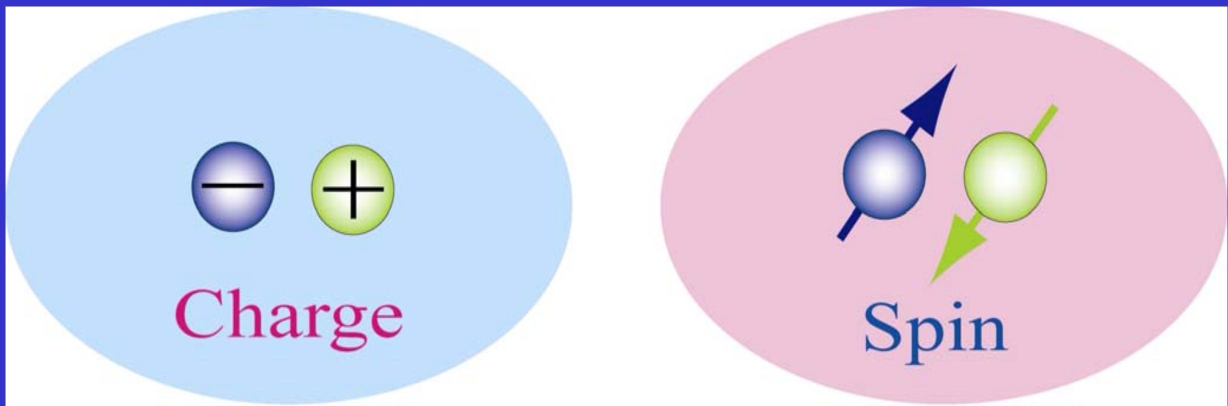
J. Am. Chem. Soc. **130** (2008) 8101

The continuous equation for PL intensity is found to hold in the time trance of isolated and bundled tubes.

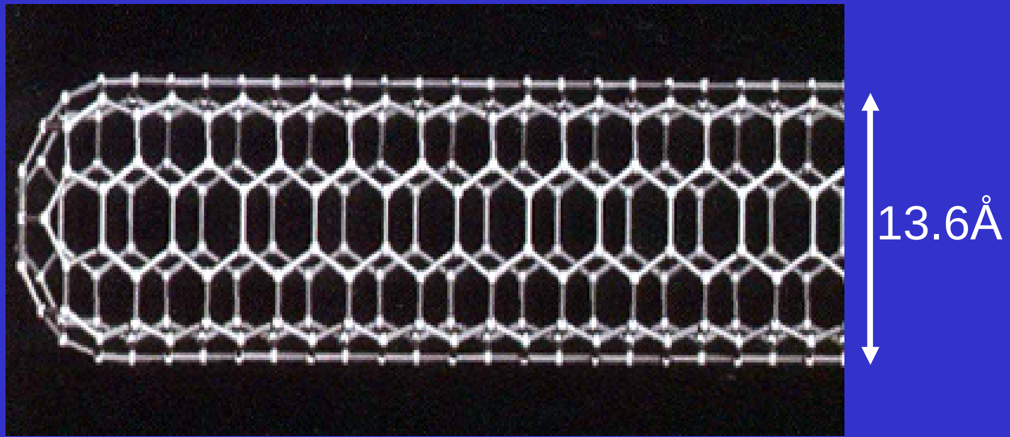
Exciton energies transfer from isolated to bundled tubes caused the PL brightening.

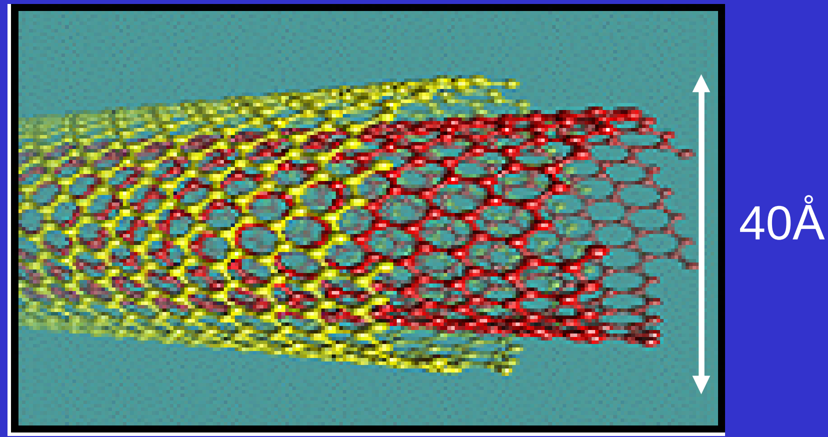
3. Inner Nano – Space Control of Carbon Nanotubes Based on Fundamental Plasma Physics

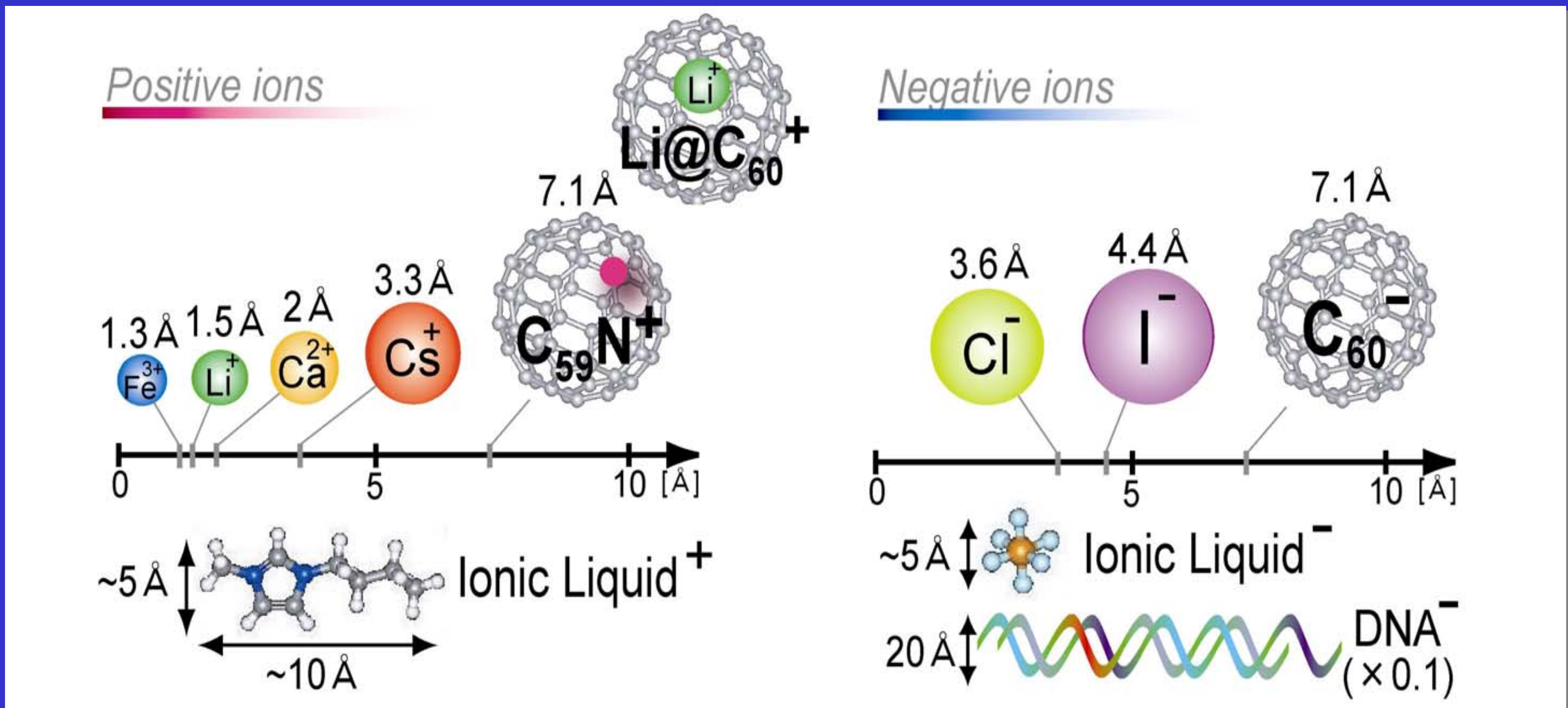
"Charge and Spin of Electrons are expected to be effectively exploited"



Formation of Atom / Molecule Encapsulated Single- and Double-Walled Carbon Nanotubes Using Different-Polarity Ion Plasmas

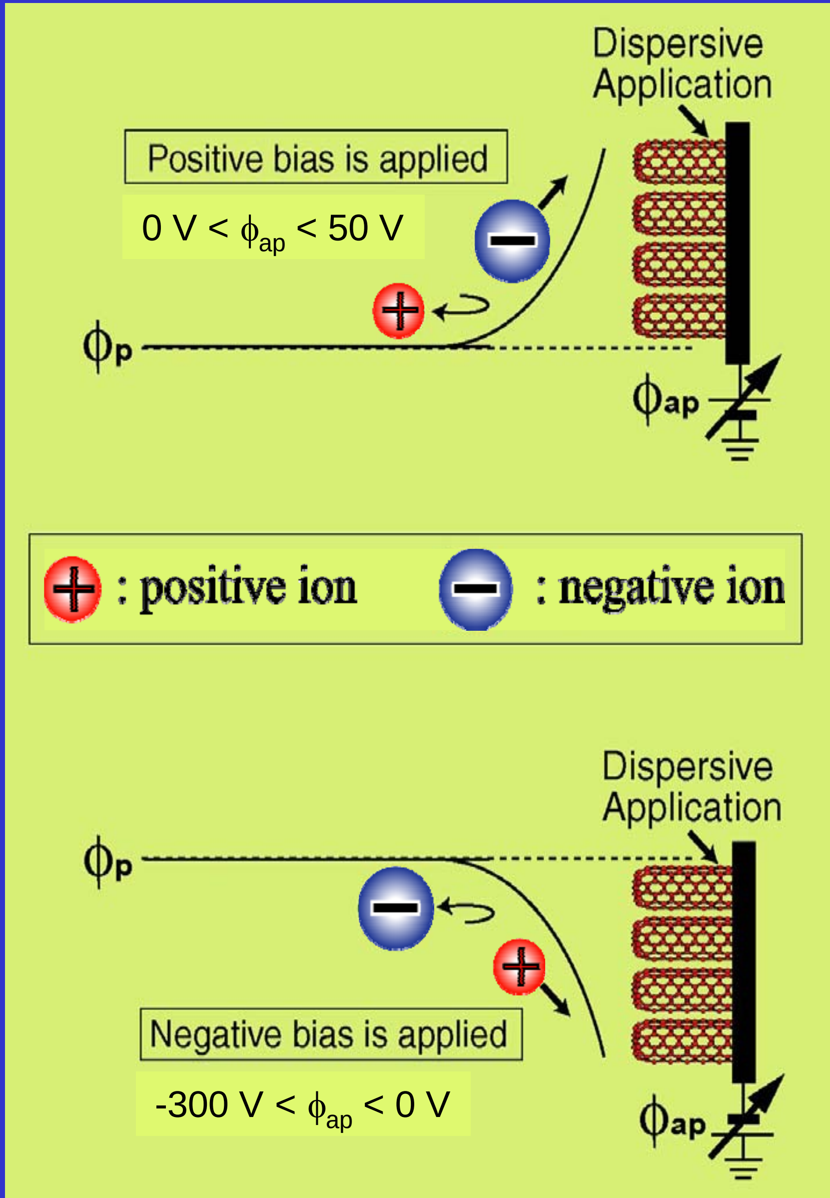






Plasma Experimental Method

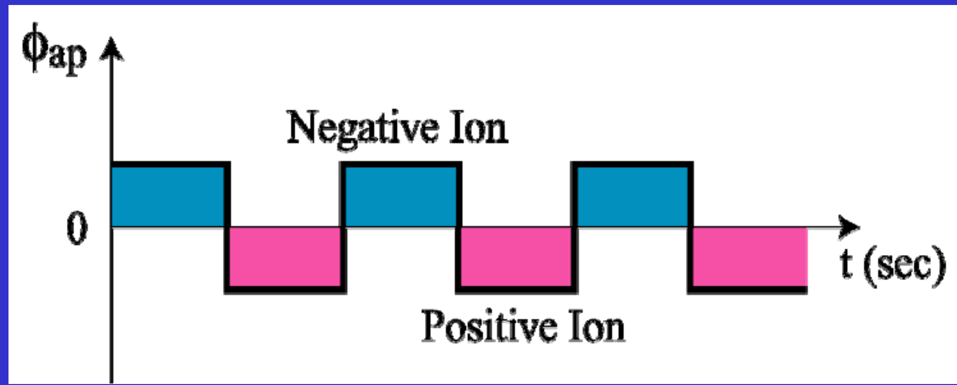
Stationary Operation



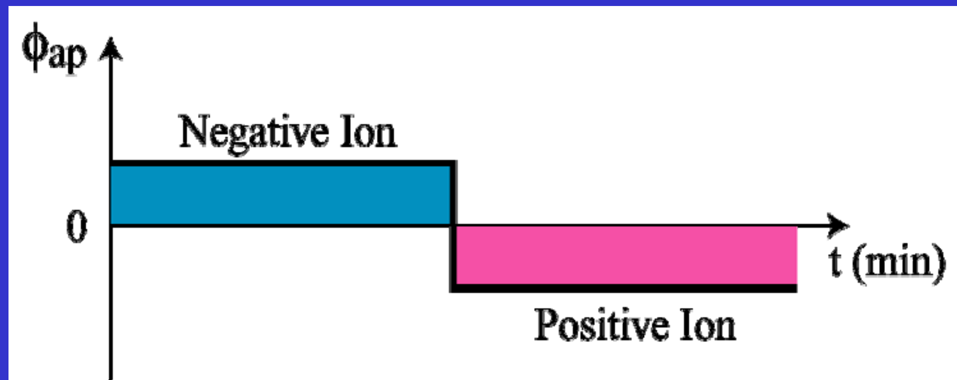
SWNTs/DWNTs

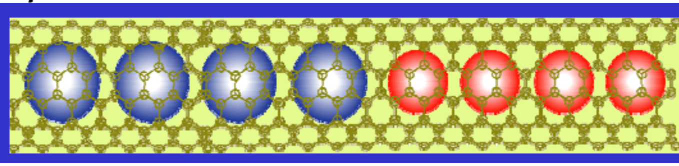
Pulsed Operation

Compound Formation inside SWNT/DWNT

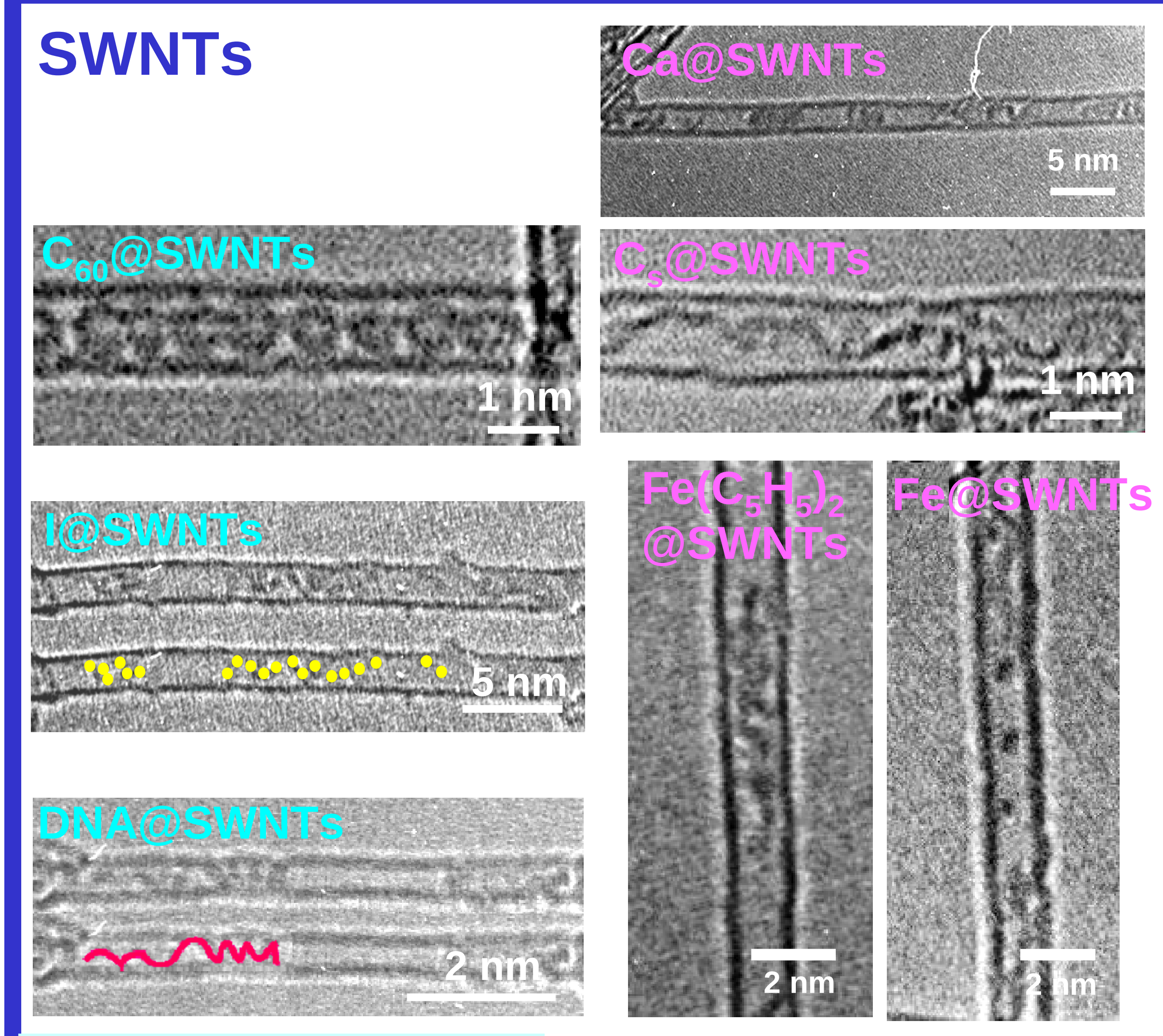


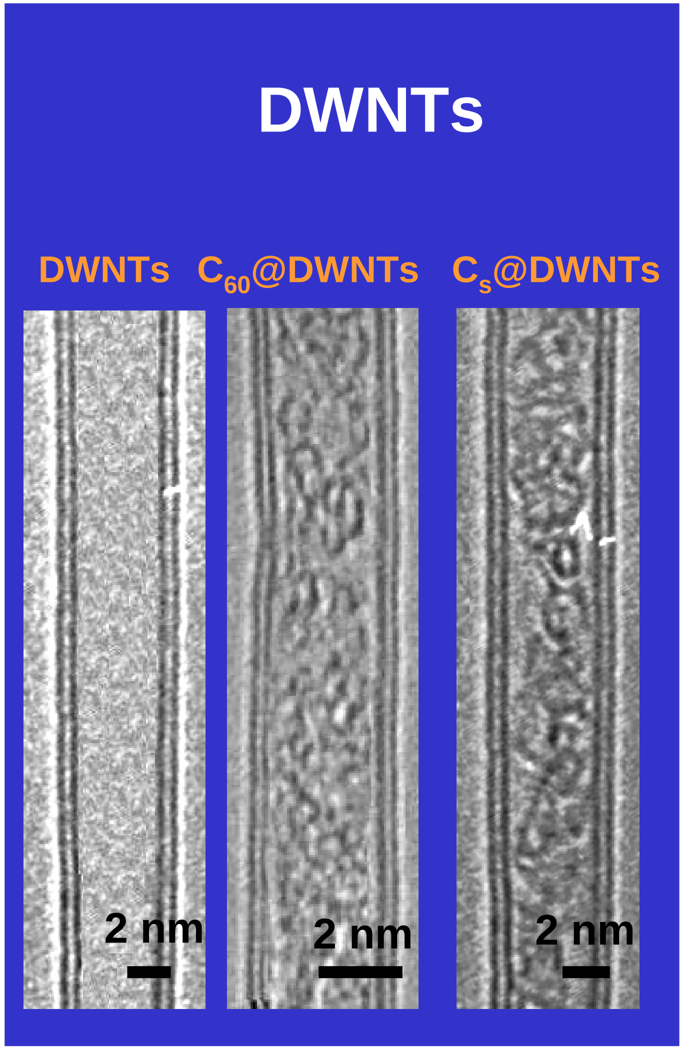
Junction Formation inside SWNT/DWNT





TEM Images of Atoms and Molecules Encapsulated SWNTs / DWNTs





Phys. Rev. B **68** (2003) 075410

Appl. Phys. Lett. **79** (2001) 4213 Chem. Commun. **1** (2003) 152

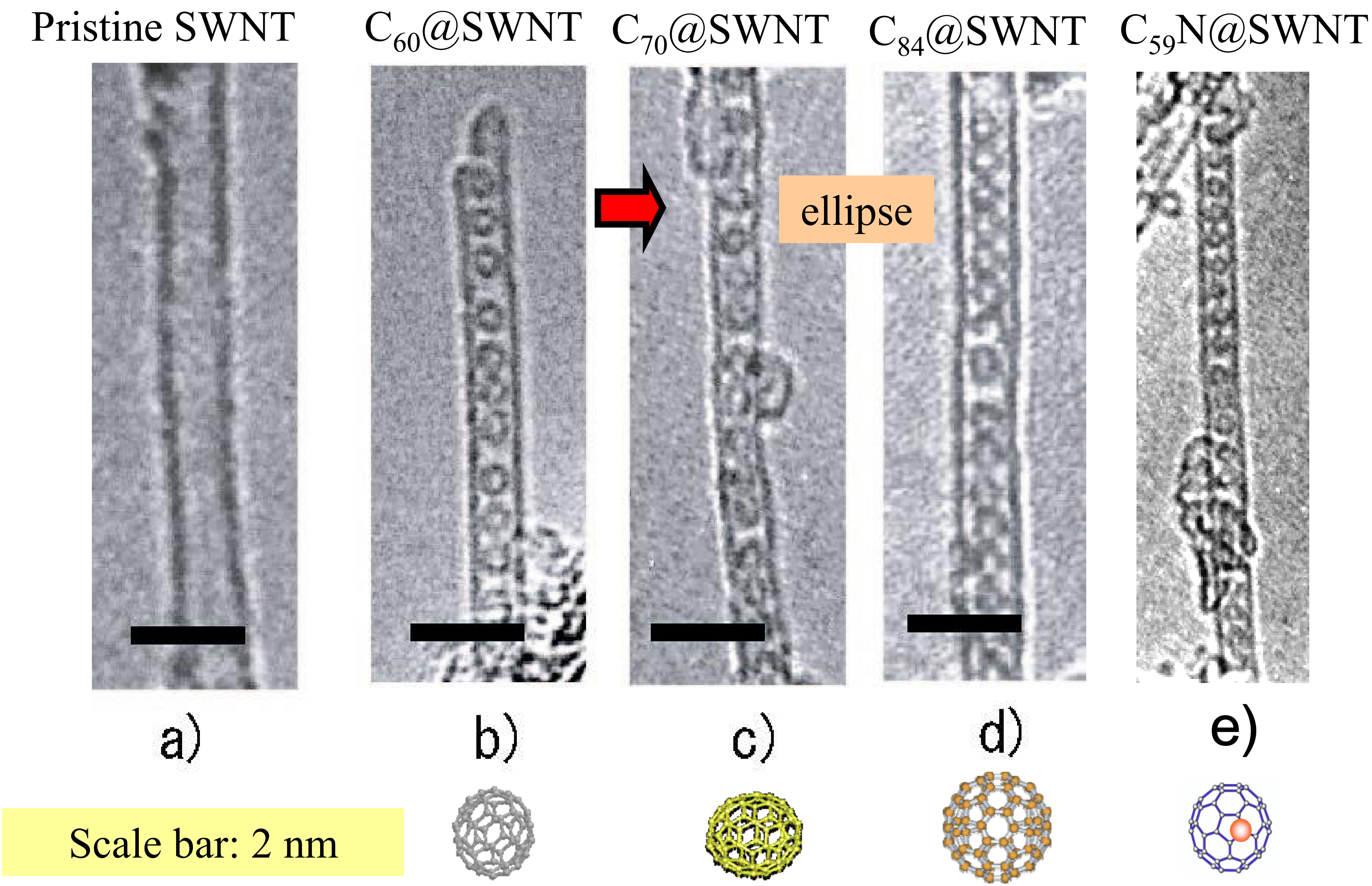
Chem. Phys. Lett. **417** (2006) 288; Jpn. J. Appl. Phys. 45 (2006) 8335

Appl. Phys. Lett. 89 (2006) 093110

Thin Solid Films 464-465 (2004) 299

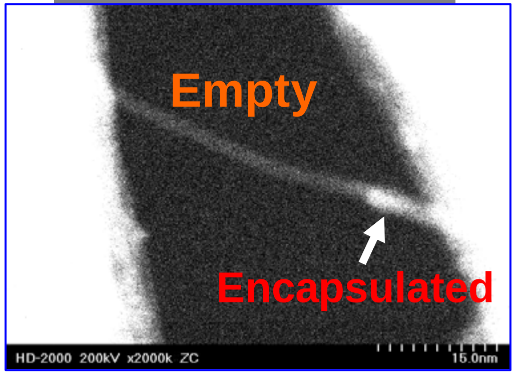
Jpn. J. Appl. Phys. 45 (2006) L428

TEM Images of Pristine and Various Fullerenes Encapsulated SWNTs

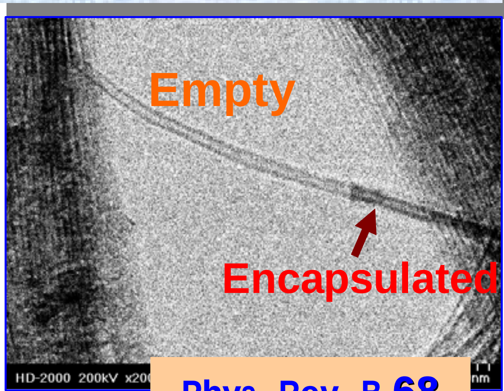


Electronic Structure inside Atom Encapsulated SWNT

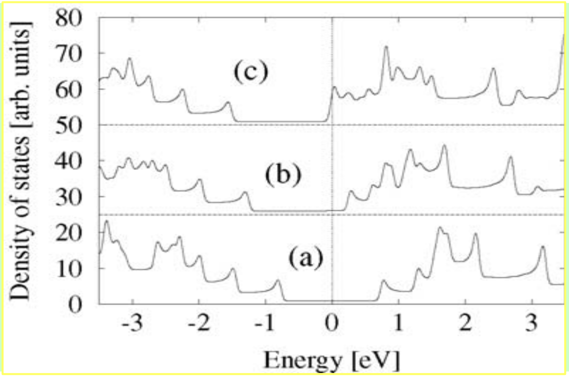
Z-contrast image



Bright field STEM image

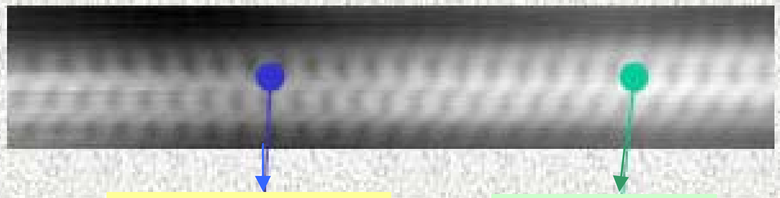


Phys. Rev. B **68** (2003) 075410



Theoretical calculation!

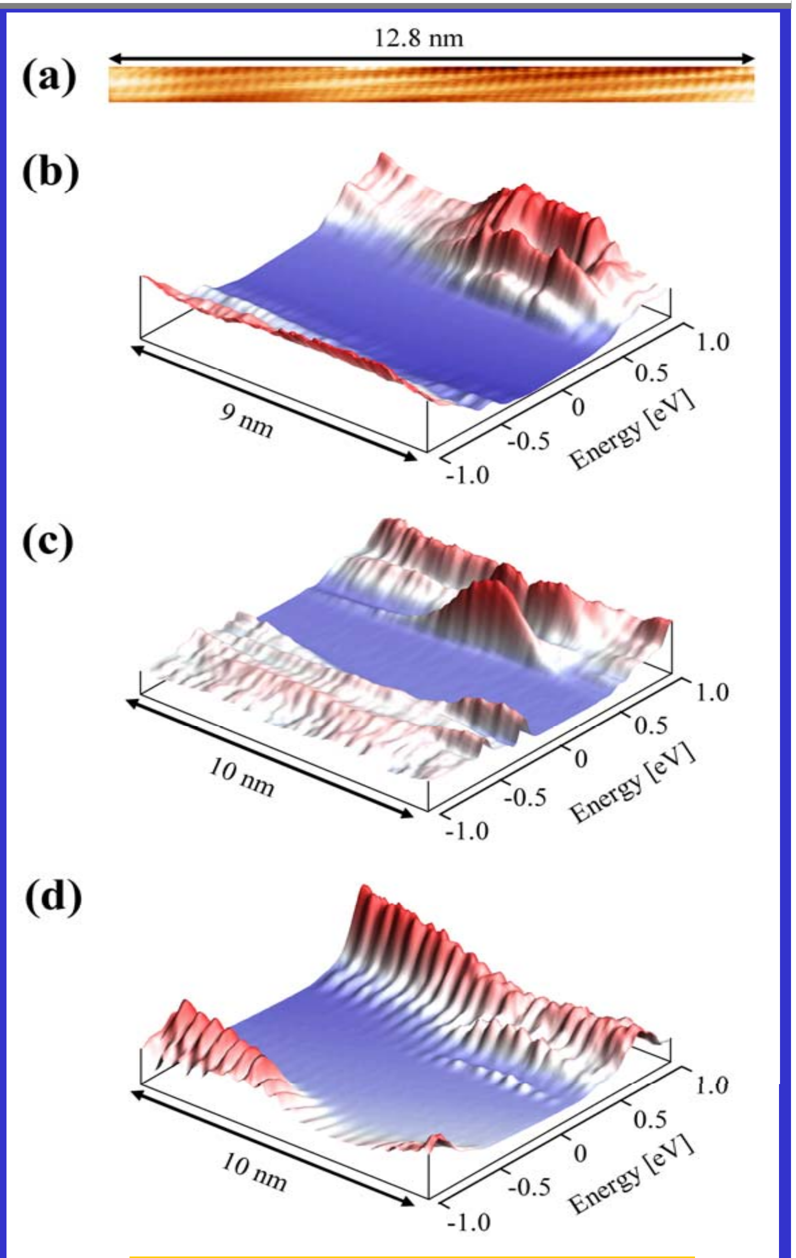
STS / STM Result



Cs unfilled

Cs filled

Collaboration with Y. Kuk' group

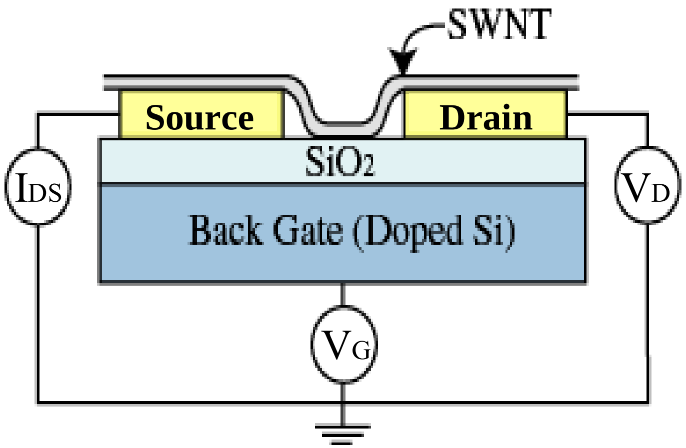


Phys. Rev. Lett. **99** (2007) 256407

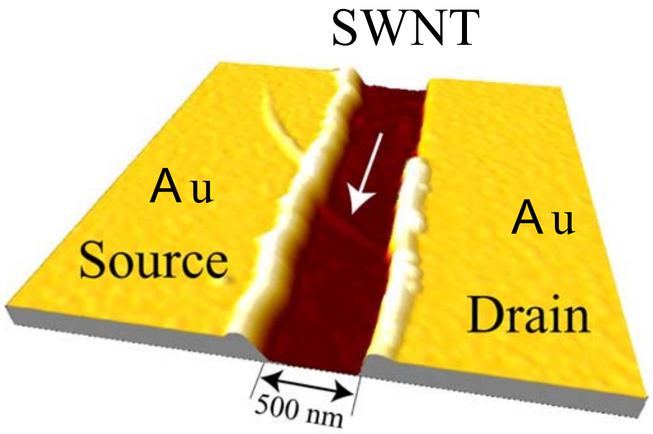
4. Electromagnetic Properties of Atom/Molecule Encapsulated Carbon Nanotubes

4.1 Control of Semiconducting Properties of Single-Walled Carbon Nanotubes

Field-Effect Transistors (FETs) Based on SWNT

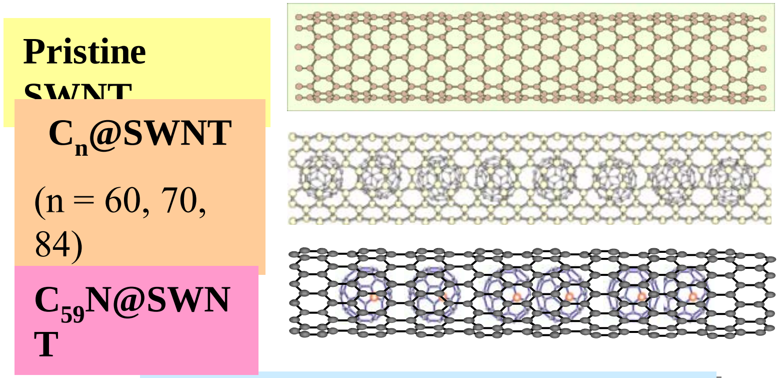


A schematic of SWNT-FET

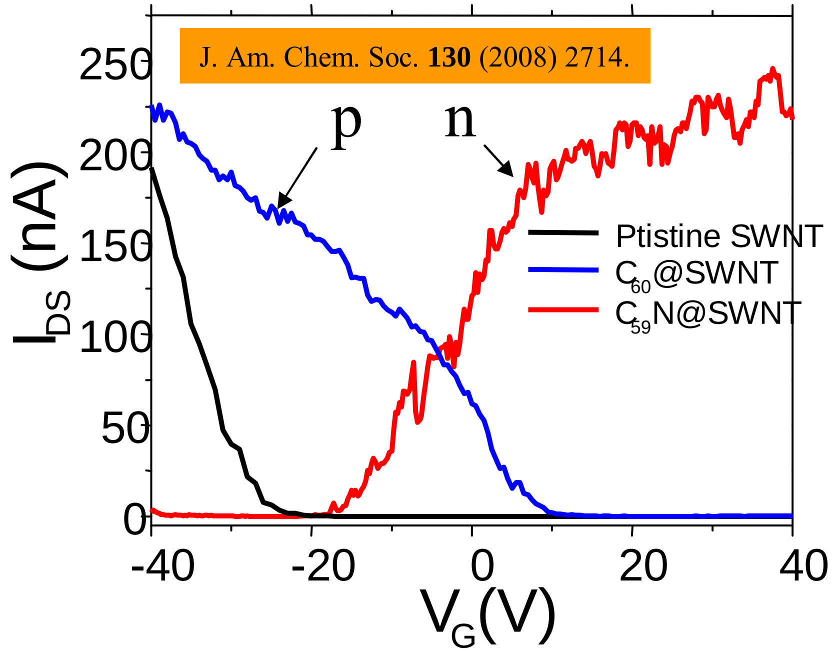


An AFM image of SWNT- FET

Jpn. J. Appl. Phys. **44** (2005) 1606



I_{DS} - V_G characteristics
(V_{DS} = 1 V, in vacuum, at 297 K)

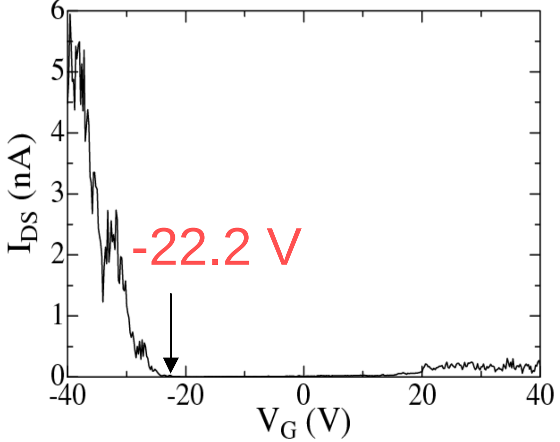


p- and n-type transport properties appear.

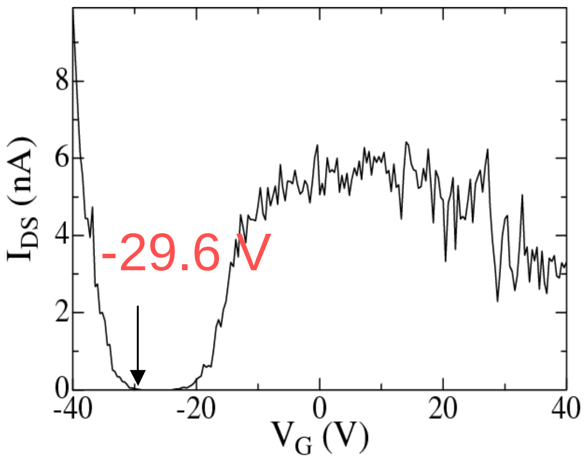
Dependence of Ion Dose on Electrical Characteristics of Cs@SWNTs

Transport Properties of Cs@SWNT
(In Vacuum, Room Temp., V_{DS} = 1 V)

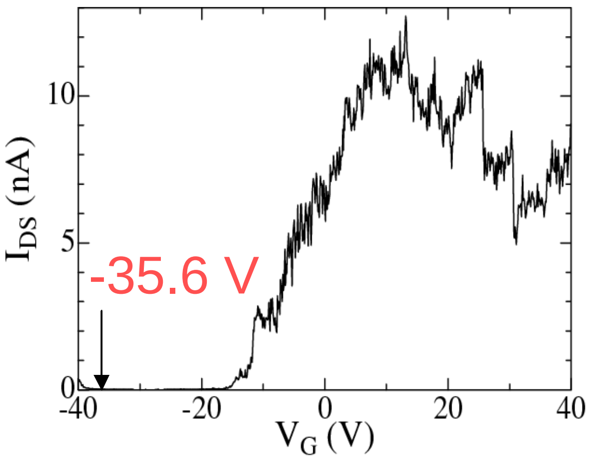
15 min
D = 2.2×10⁴ /nm²



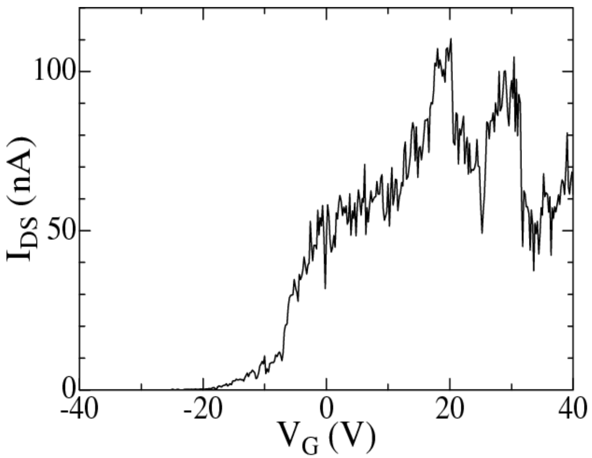
30 min
D = 4.3×10⁴ /nm²

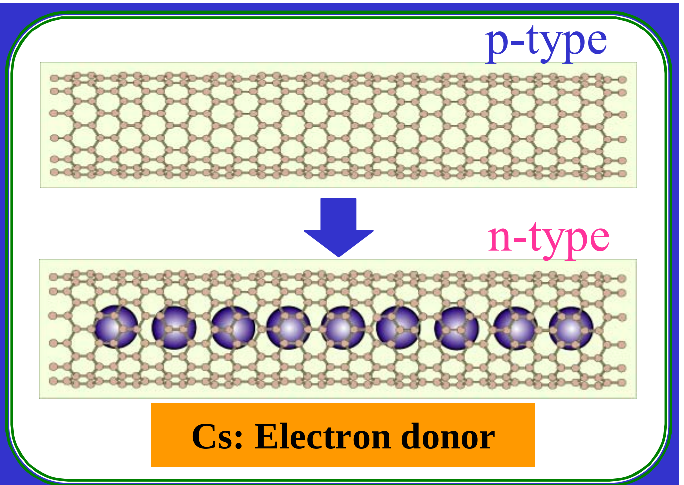


45 min
D = 6.5×10⁴ /nm²



60 min
D = 8.6×10⁴ /nm²





- As the amount of dosed Cs increases, the threshold for *p*-type shifts left.
- After 60 min Cs irradiation Cs@SWNT shows completely *n*-type behavior.

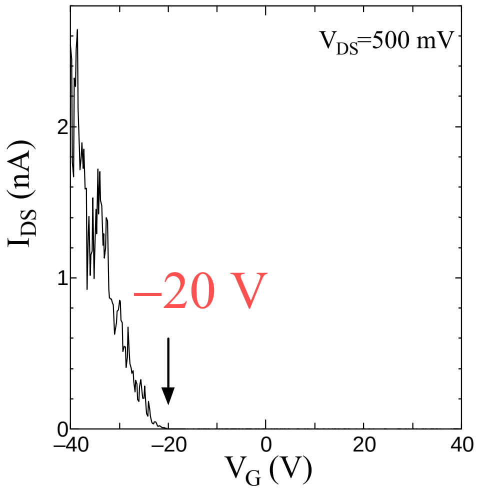
Electronic structure of SWNT can be controlled by adjusting an amount of dosed Cs atoms.

Appl. Phys. Lett. **89** (2006) 093121

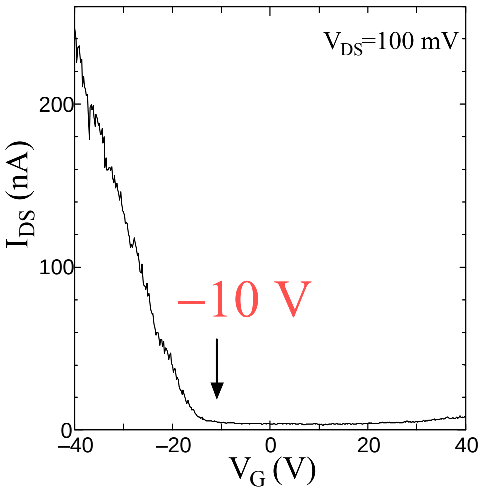
Dependence of Ion Dose on Electrical Characteristics of I@SWNT

Transport Properties of I @SWNT (In Vacuum , Room Temp.)

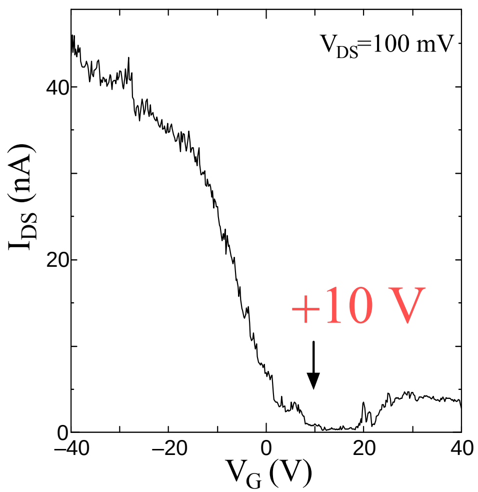
30 min



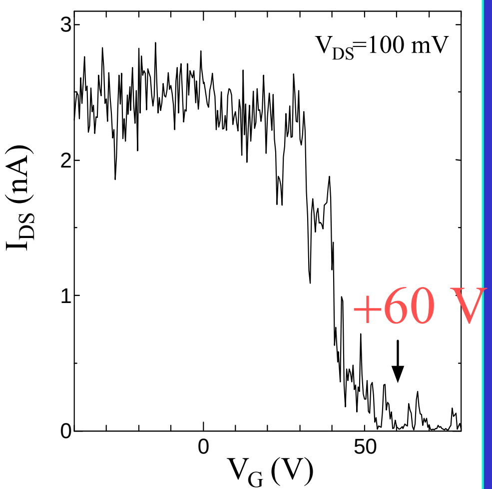
60 min



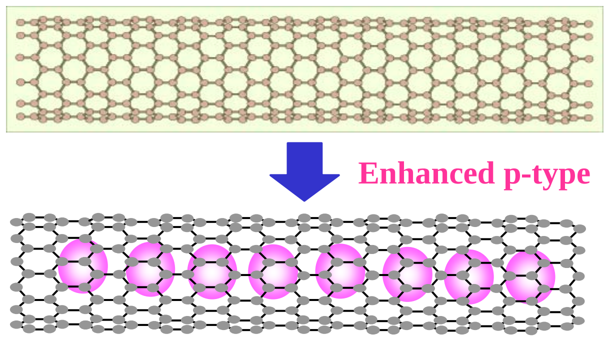
120 min



240 min



Jpn. J. Appl. Phys., **47** (2008) 2044

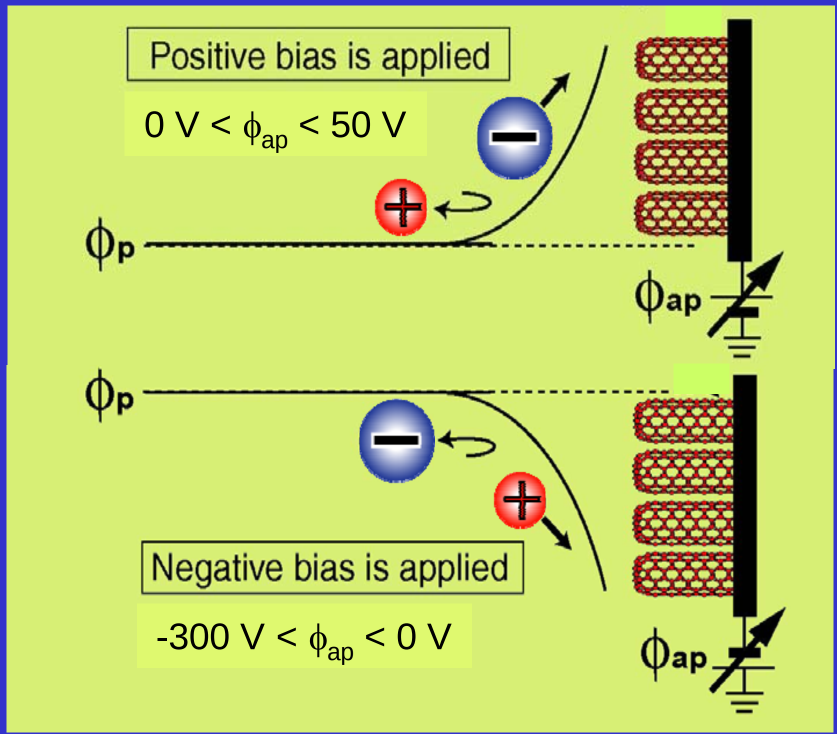


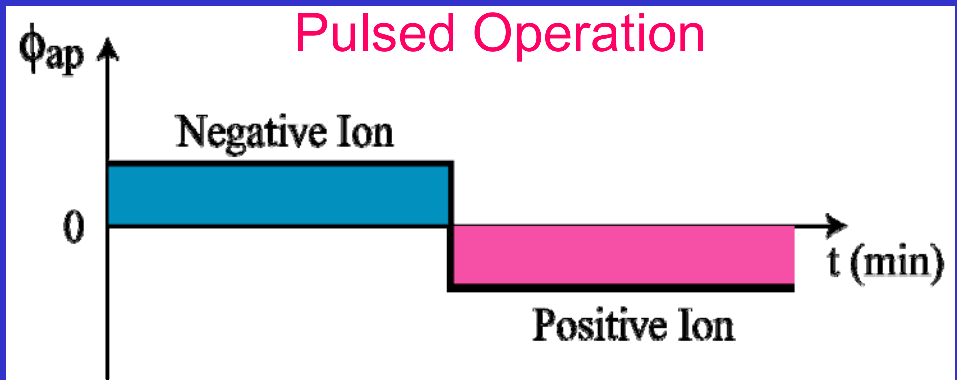
I: Electron acceptor

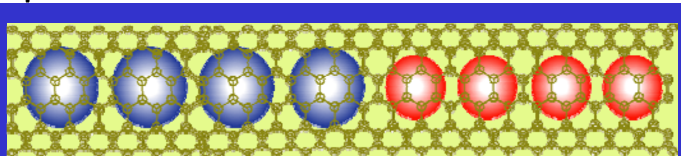
- As the amount of dosed I increases, the threshold for *p*-type shifts right.
- After 240 min I irradiation I@SWNT shows a clear enhanced *p*-type behavior with threshold at 60 V.

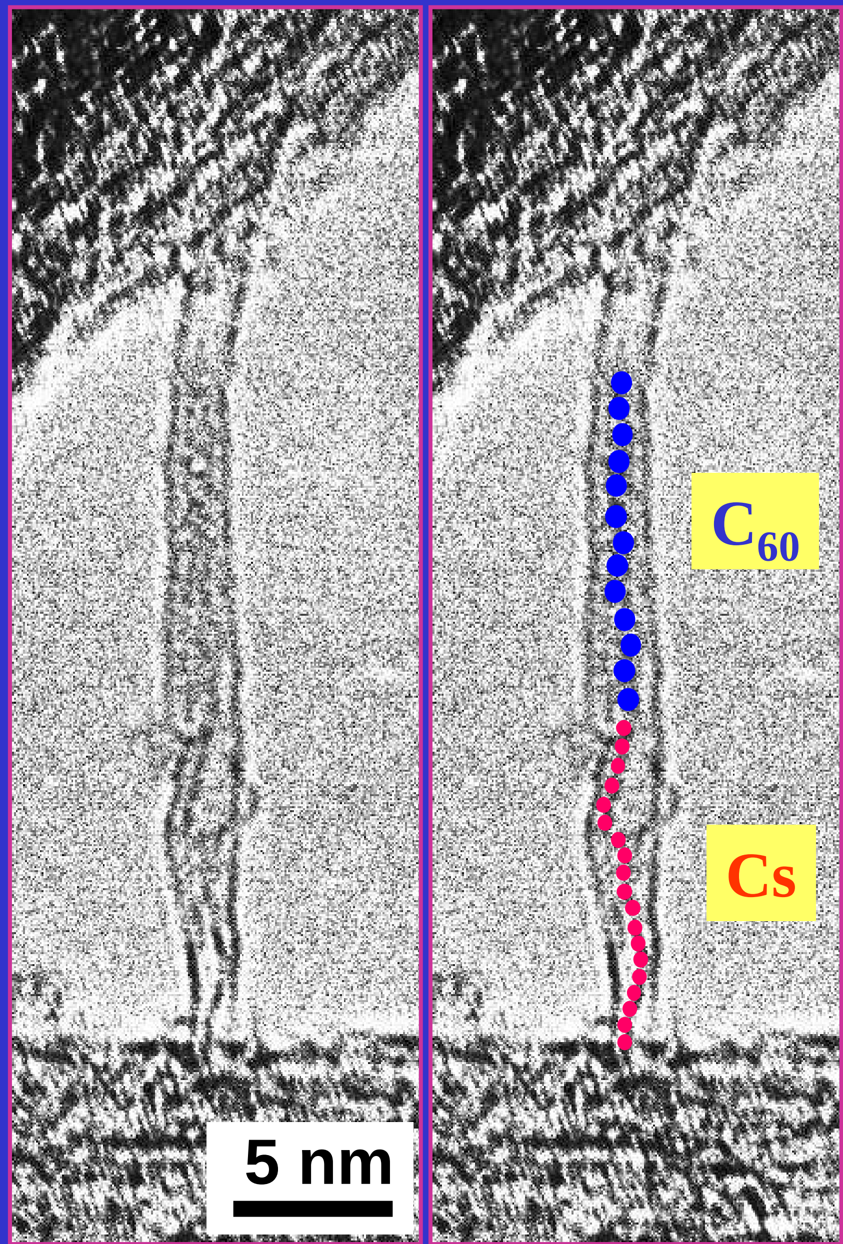
4.2 Formation of Nano *pn* Junctions by Controlling Different-Polarity Ion Plasmas

Controlled Formation of Nano pn Junctions [$(Cs/C_{60})@SWNT$]

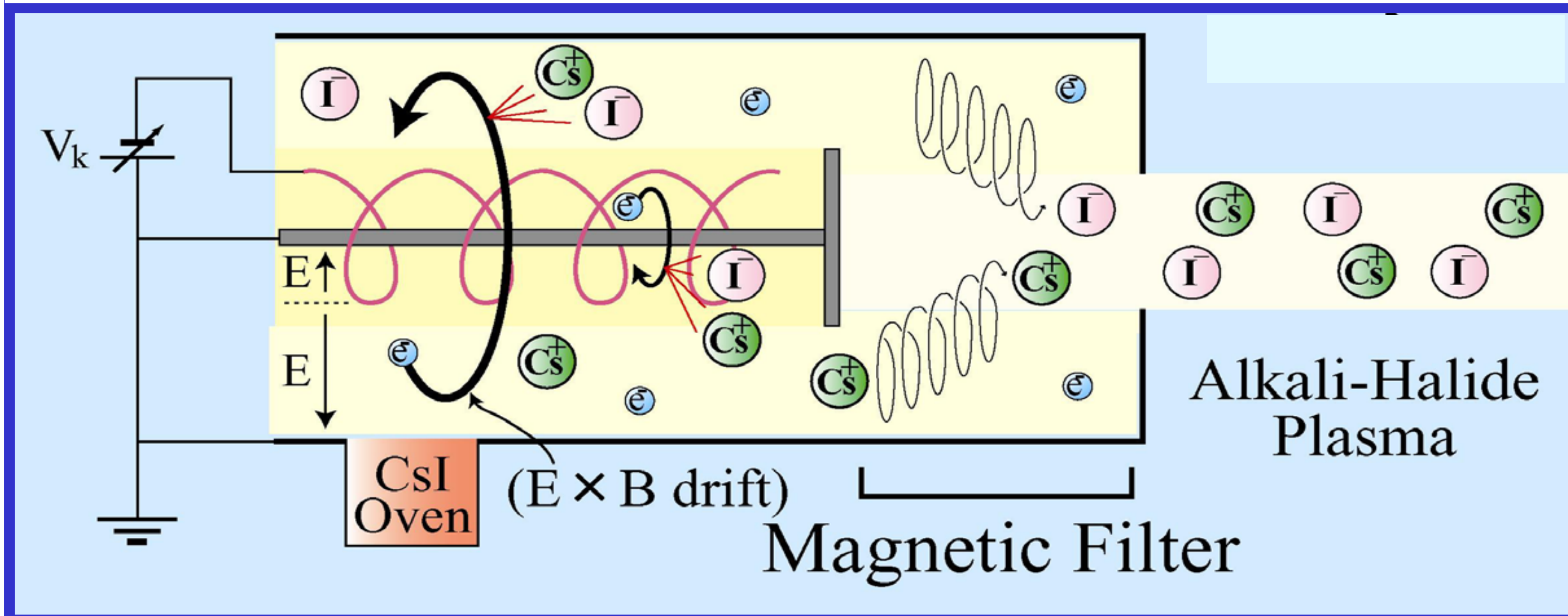




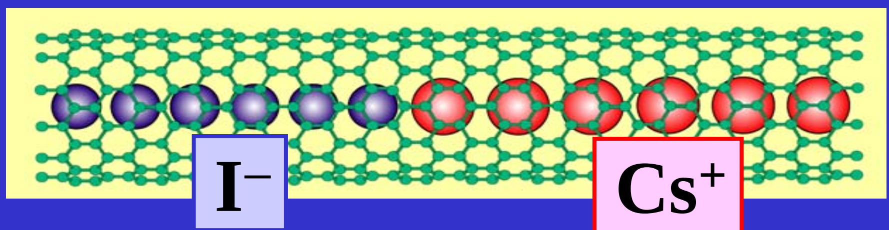


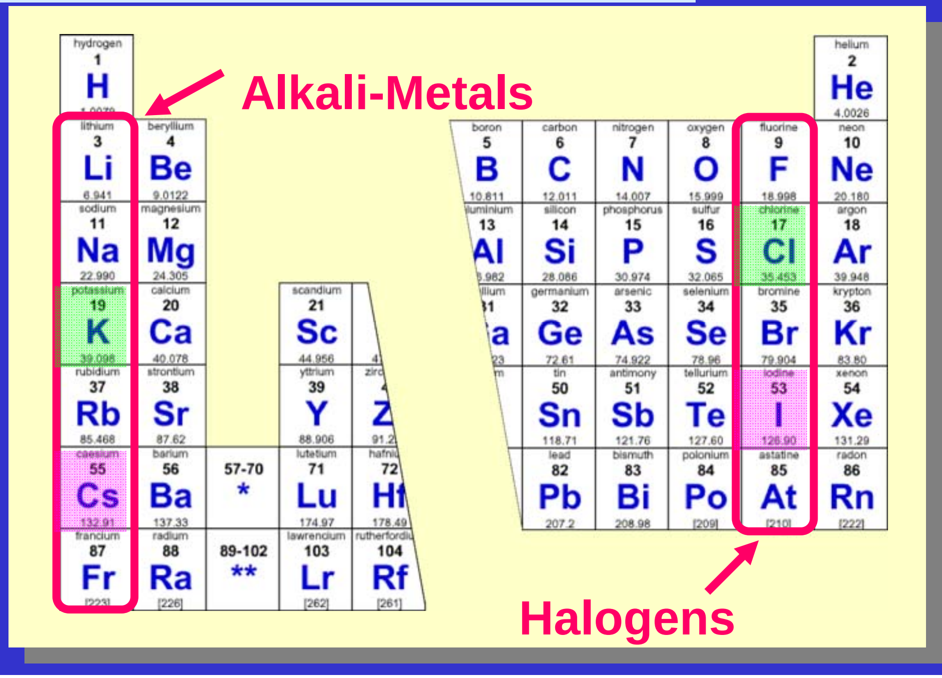


Using Alkali-Halogen (Cs^+ - I^-) Plasma

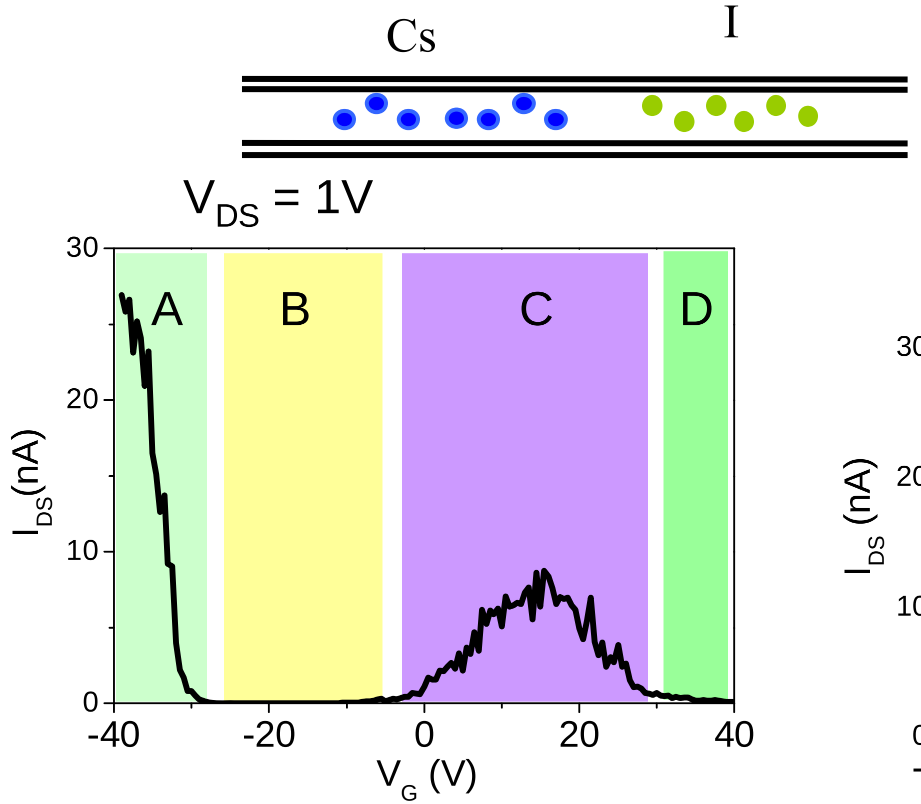


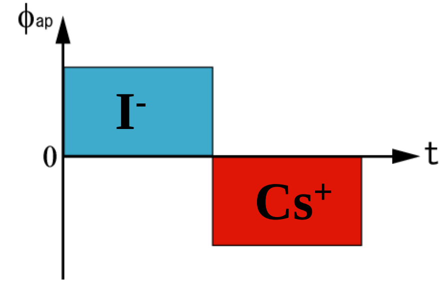
Nano pn Junction

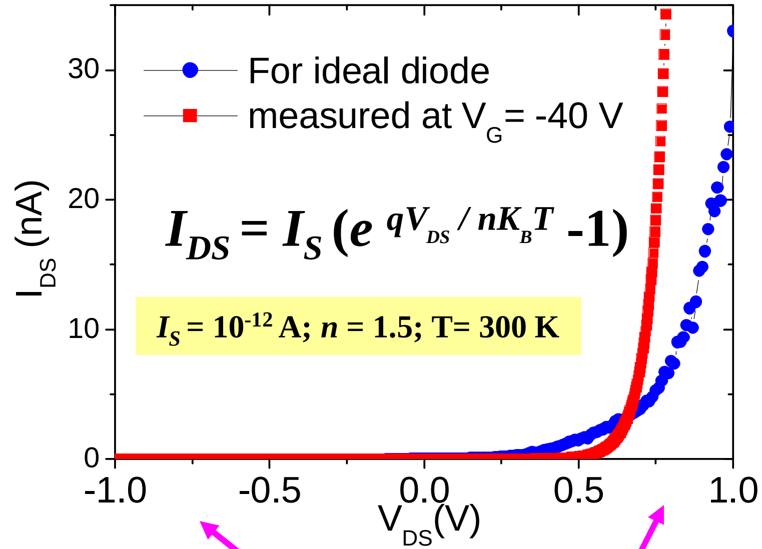


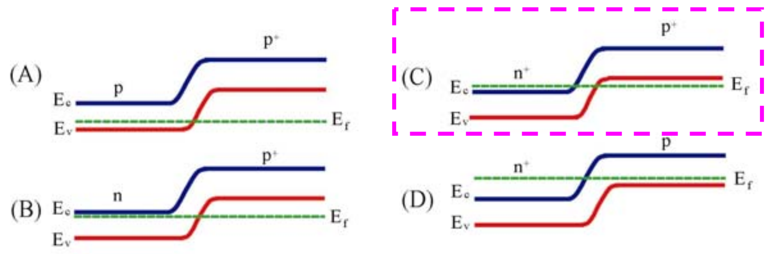


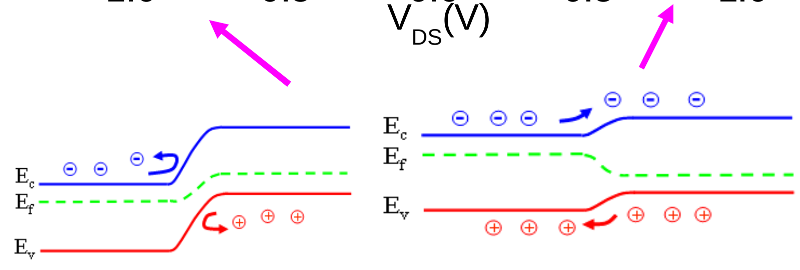
Nano pn Junction Formed by (Cs/I) @ DWNT





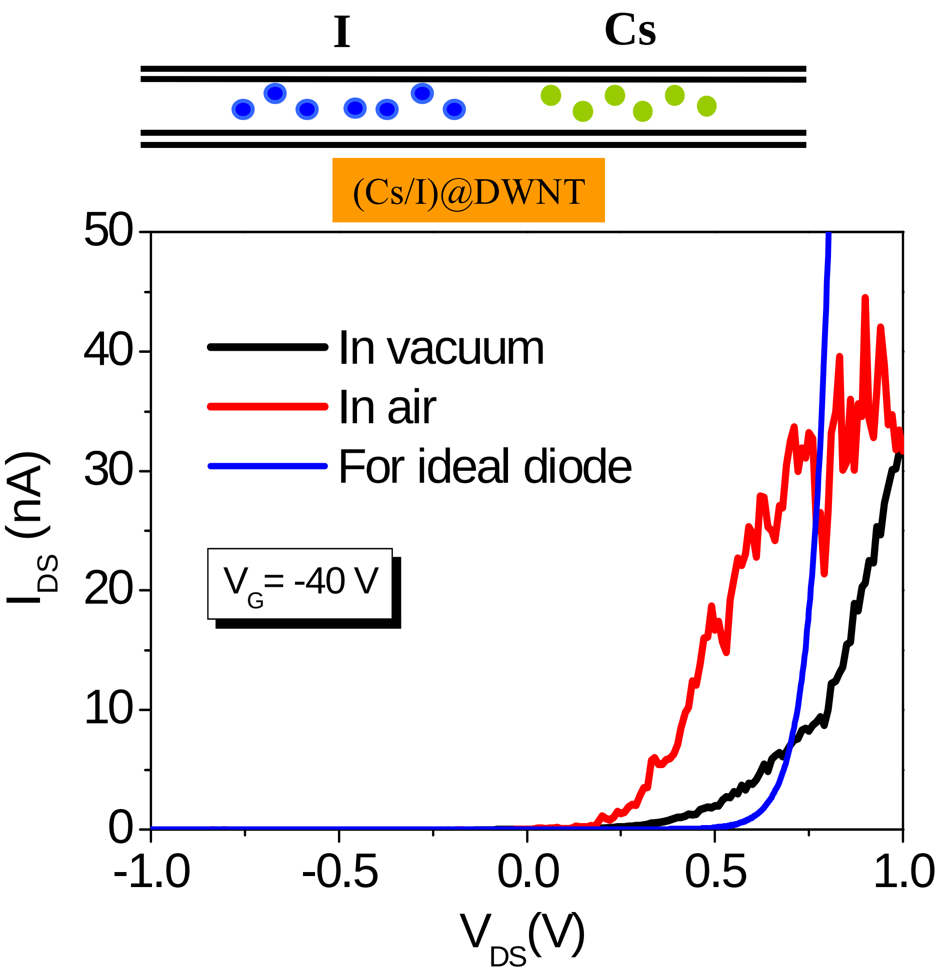


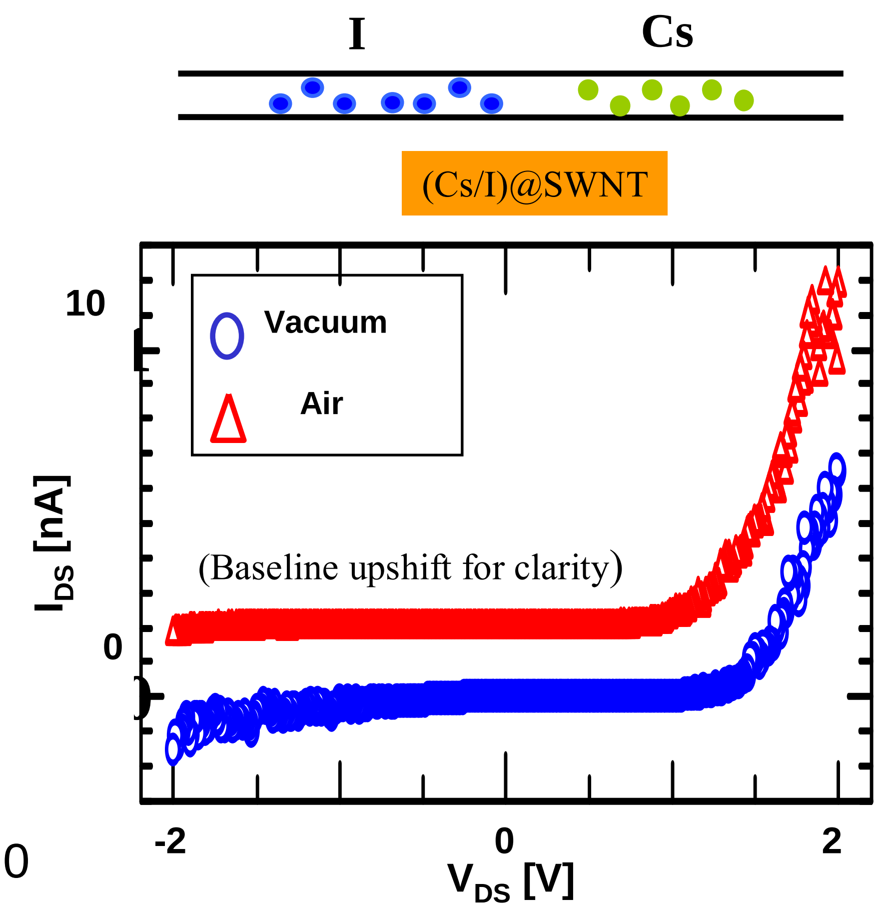




Video link

Nano pn Junction with stable rectifying behavior of (Cs/I)@DWNT and (Cs/I)@SWNT in air





Output characteristics keep stable even in air, indicating p-n junction in SWNTs & DWNTs with high-performance can be fabricated by hetero-atoms or -molecules encapsulation.

4.3 Coulomb Oscillation Characteristics of Encapsulated Carbon Nanotube

– Quantum Dot Formation –

Coulomb oscillation

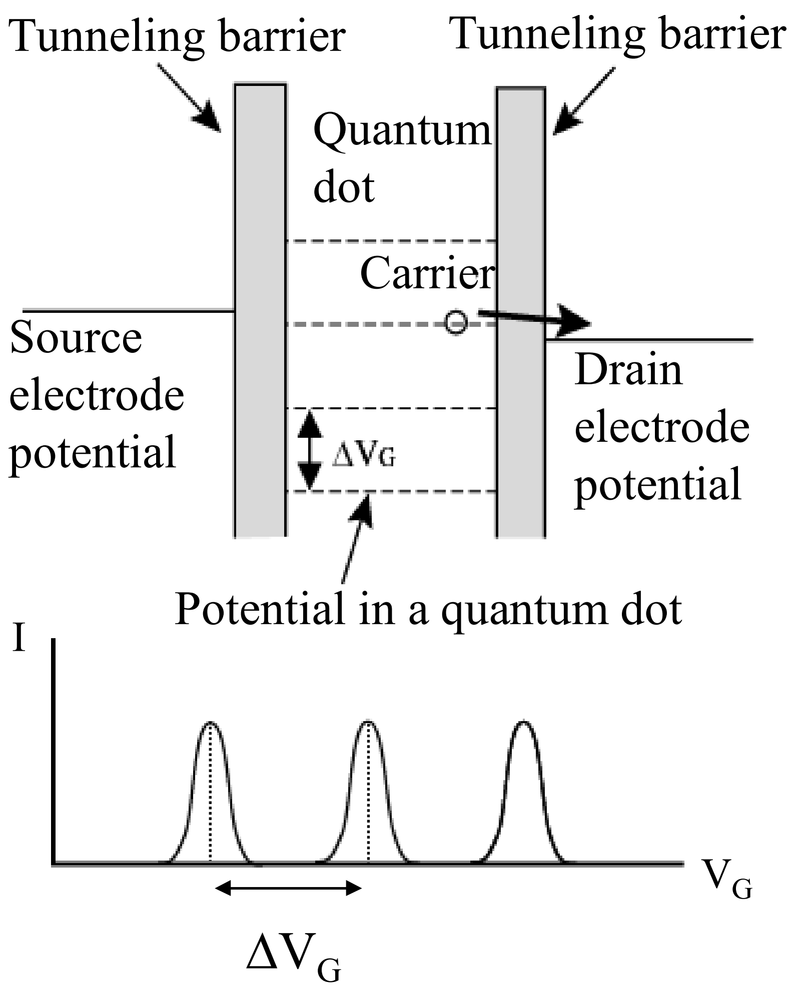


Fig. : Quantum dot and Coulomb oscillation formed by a single dot

The energy level is quantized in a quantum dot

The static energy level in quantum dot can be controlled by externally applied V_G (V_{DS} : constant)

Current through only when the quantum energy level matches with the fermi energy of drain electrode

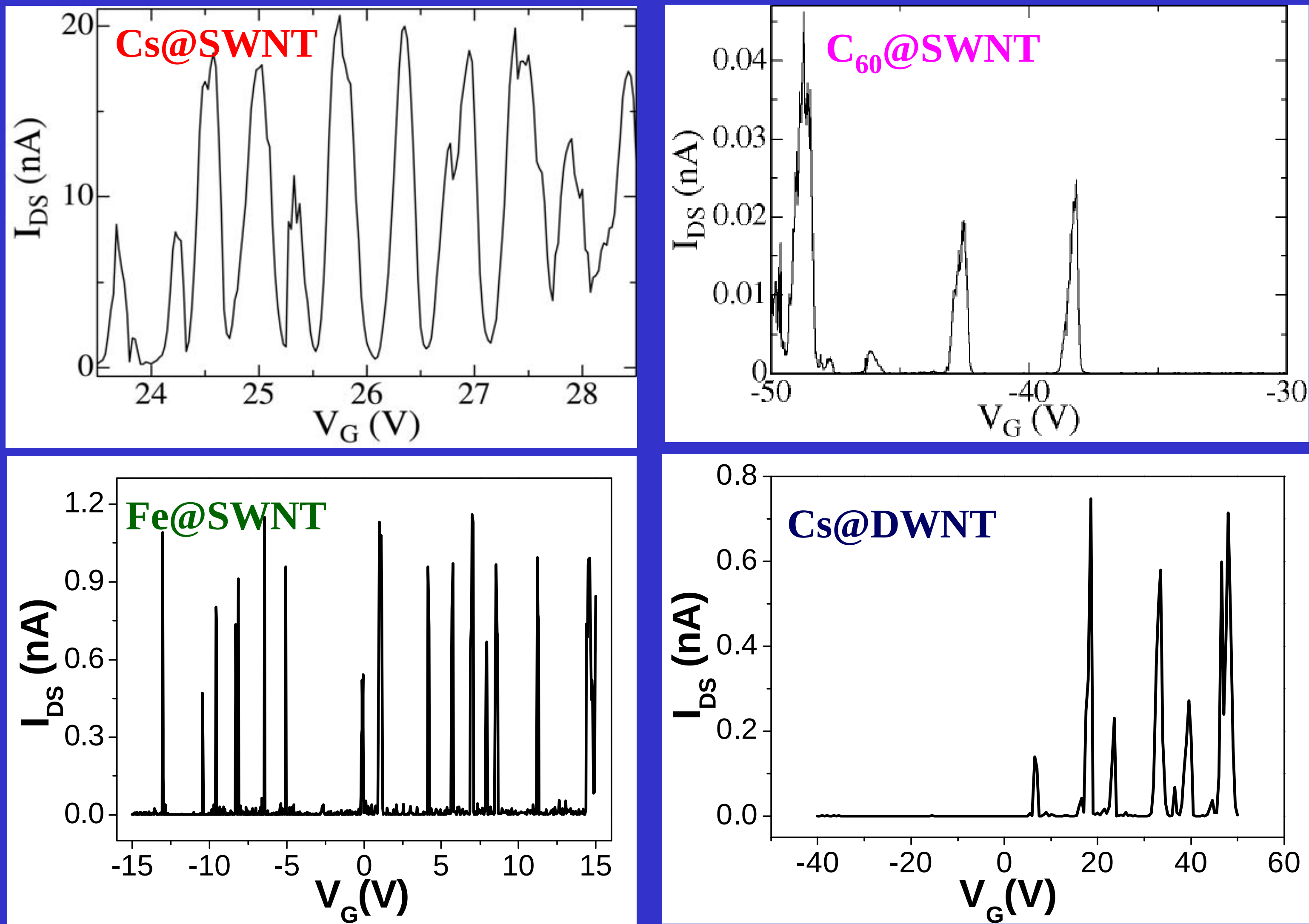
The quantum dot size can be estimated with the Coulomb oscillation

$$C_g = \frac{e}{\Delta V_G} \approx \frac{2\pi\varepsilon_0 L}{\ln(2L/d)}$$

L: Dot size
d: SWNT diameter

Investigate the effect of alkali-atom encapsulation on SWNTs

Coulomb Oscillations Observed in Encapsulated Nanotubes



Quantum dots formed in nanotubes due to foreign materials encapsulation.

Summary

Historical evolutions over 50 years of Q-machine plasma researches are reviewed, where a special emphasis is placed on experimental methodologies of sheared-flow and nano-quantum physics.

Following the drift-wave studies on superposition effects of parallel and perpendicular flow velocity shears and hybrid ions flow velocity shears, an experiment on electron temperature gradient (ETG) instabilities is started, where the large ETG is successfully generated with the radial density profile kept uniform using thermionic electron superimposed ECR plasma.

The innovative transformation of Q machine plasmas for nano physics and chemistry studies has been performed in order to create novel nano-structures and new functional nano-materials by controlling inner nano-spaces of fullerenes and carbon nanotubes.

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Committees

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Head Office: (Attn. to Prof. Kazuaki Hanada) Advanced Fusion Research Center, Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan Tel : +81-92-583-7706 Fax : +81-92-573-6899 E-mail : icpp2008@triam.kyushu-u.ac.jp

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ISGLP2008

International Interdisciplinary-Symposium on Gaseous and Liquid Plasmas

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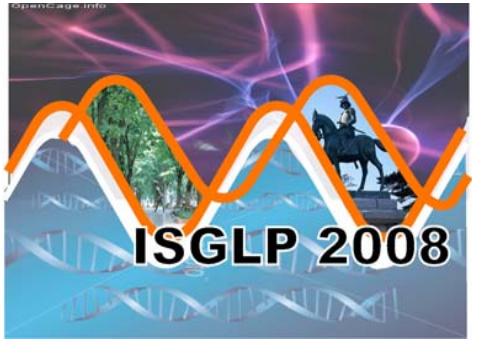
Tohoku University
Akiu / Sendai, Japan

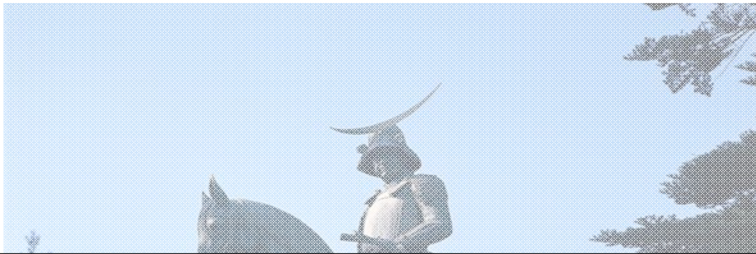
http://www.plasma.ecei.tohoku.ac.jp/ISGLP/

International Interdisciplinary-Symposium on Gaseous and Liquid Plasmas (ISGLP2008)



September 5-6, 2008

Tohoku University / Sendai, Japan



Calendar of Events

First announcement and call for papers	**March 2008**
One-page abstract deadline	**May 2008**
Second announcement	**June 2008**
Four-page papers deadline for a proceedings volume	**August 2008**
Final announcement/program	**August 2008**

http://www.plasma.ecei.tohoku.ac.jp/ISGLP/

Satellite Meeting of International Congress on Plasma Physics (ICPP2008)

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