AMN-3
The MacDiarmid Institute
for Advanced Materials and Nanotechnology

Study of silicon nanodot formation in pulsed-gas plasma process

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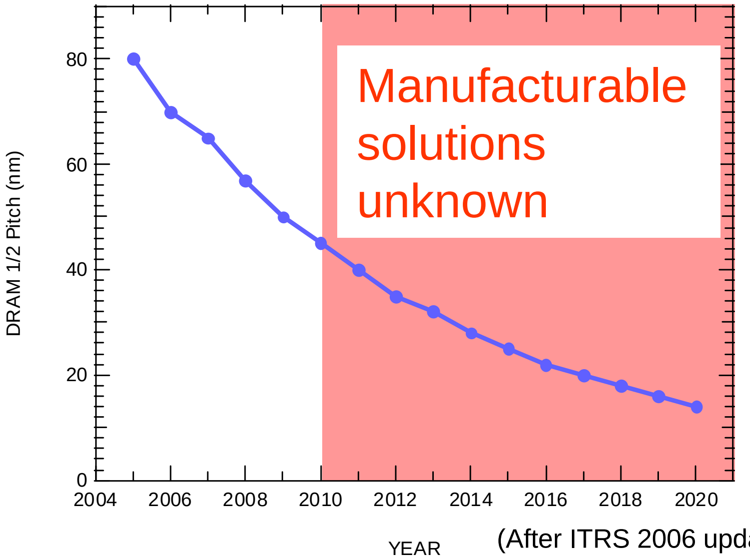
QNERC Quantum Nanoelectronics Research Center
TOKYO INSTITUTE OF TECHNOLOGY
JST

Introduction

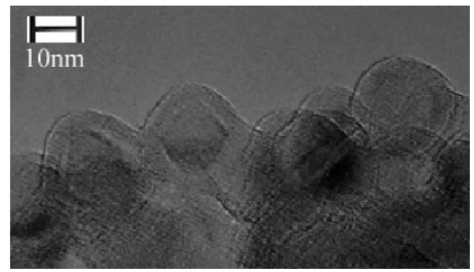
Future Silicon Nanodevices

Limit of top-down scaling → Use of bottom-up nanostructures

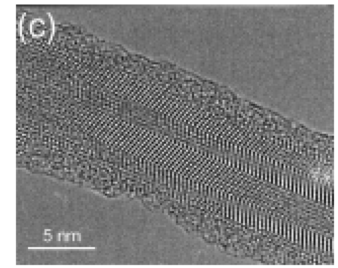


(After ITRS 2006 updated)

Silicon nanodot

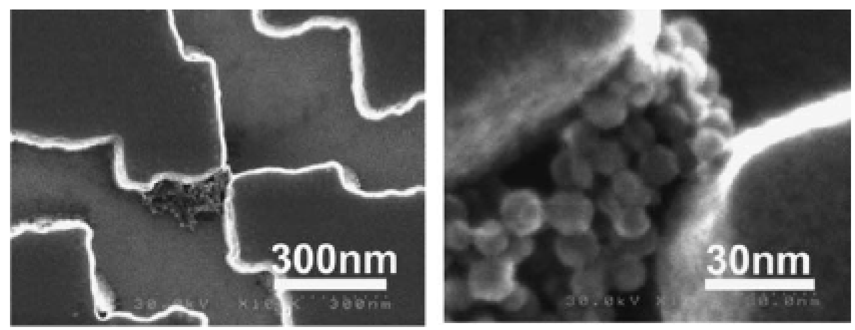


S. Oda,
Mat. Sci. Eng. **B101**, 19 (2003).



S. Hofmann *et al*.,
J. Appl. Phys. **94**, 6005 (2003).

Silicon nanowire



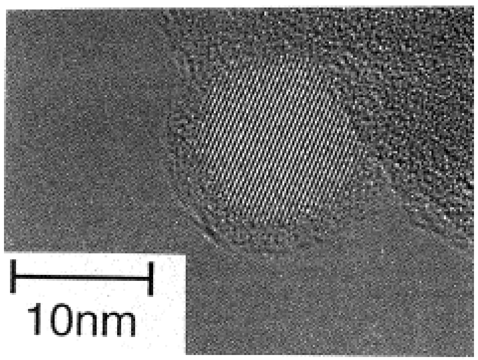
A. Tanaka *et al*., Curr. Appl. Phys. **6**, 344 (2006).

Fusion of top-down and bottom-up technologies

→ Open a new field of silicon nanodevices

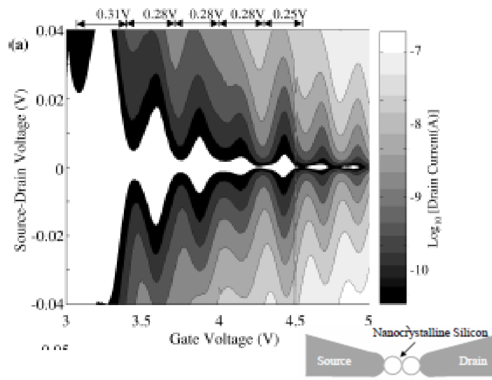
Silicon nanodots (SNDs)

Key building block for future Si nanodevices

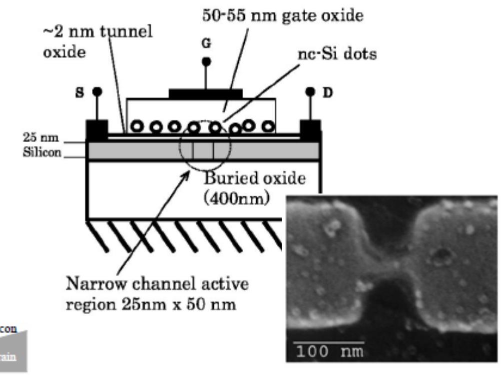


T. Ifuku *et al*., Jpn. J. Appl. Phys. **36**, 4031 (1997).

Single Electron Transistor/Memory

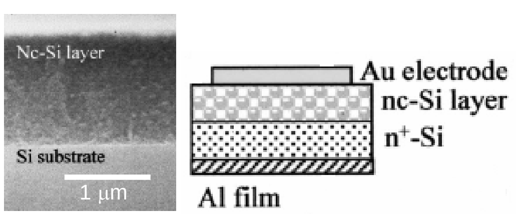


A. Dutta *et al*.,
Jpn. J. Appl. Phys. **39**, 4647 (2000).

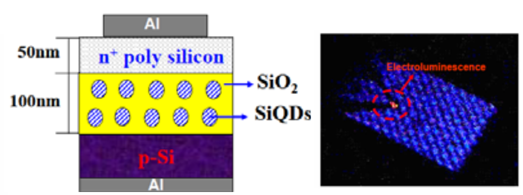


B. J. Hinds *et al*.,
J. Appl. Phys. **90**, 6402 (2001).

Electron/Light Emitter

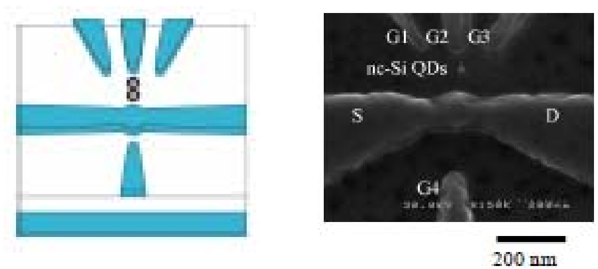


K. Nishiguchi *et al*.,
J. Appl. Phys. **92**, 2748 (2002).



H. Cheong *et al*.,
Tech. Dig. CLEO 2006 CTuN4 (2006).

Quantum Information Devices

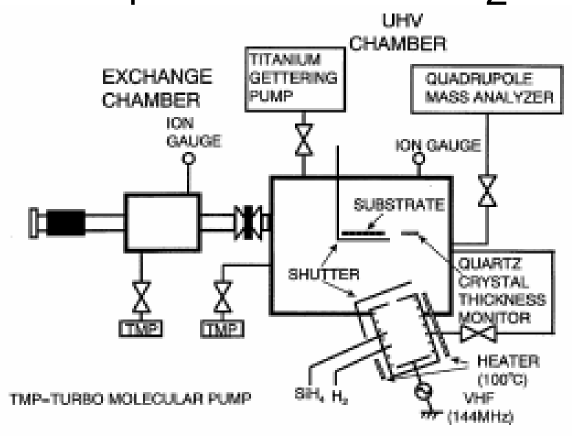


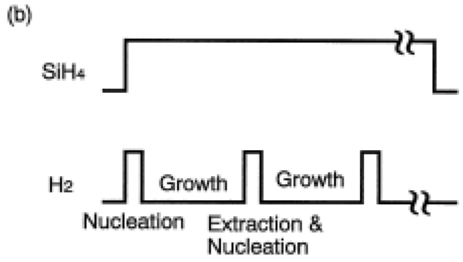
Y. Kawata *et al*., Ext. Abst. SSDM 2006, pp. 812 (2006).

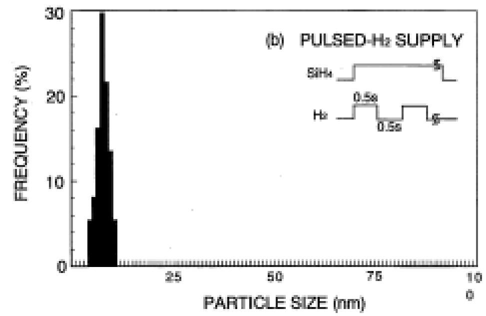
SNDs Fabrication – Pulsed Gas VHF Plasma Process

SiH_4 Plasma + H_2

T. Ifuku *et al.*, Jpn. J. Appl. Phys. **36**, 4031 (1997).



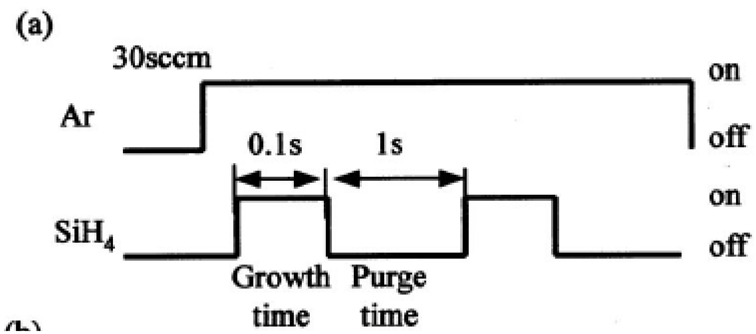


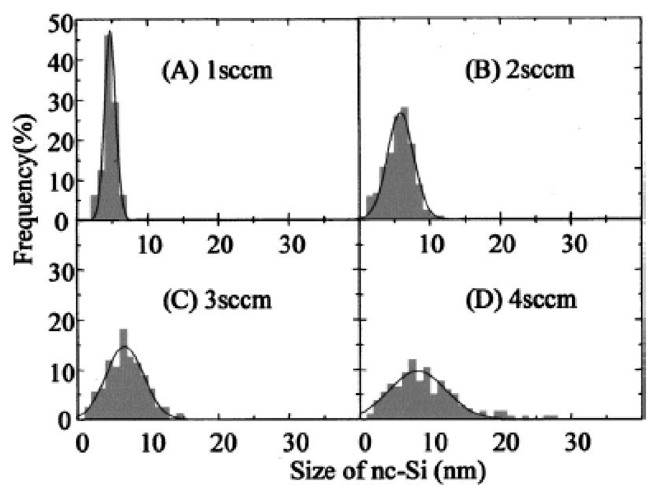


- Nucleation and growth time control
- Diameter around 8±1 nm achieved

Ar Plasma + SiH_4

K. Nishiguchi *et al.*, J. Appl. Phys. **92**, 2748 (2002).



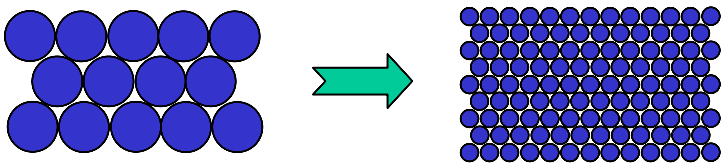


- Faster deposition rate with keeping mono-dispersion

Technical challenge

Further miniaturization

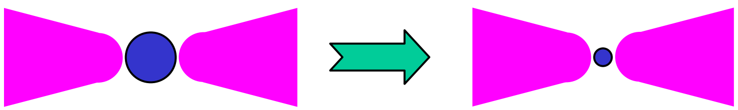
High density assembly



Large ΔV_{th} for non-volatile memory

High efficiency in electron emitter

Increasing charging and quantum confinement energies



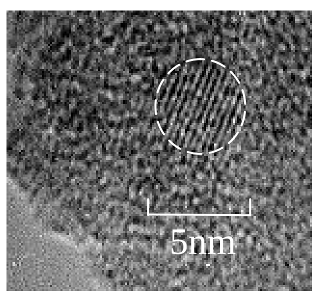
High temperature operation of SET or quantum information devices

Blue shift of emitting light wavelength

Surface oxidation

(750 ℃ 15hs)

J. Ohmachi *et al.*, Mat. Res. Soc. Symp. Proc. **638,** F5.3 1-6 (2001).



Thick oxide surrounded

In situ growth of small SNDs with higher deposition rate is preferable

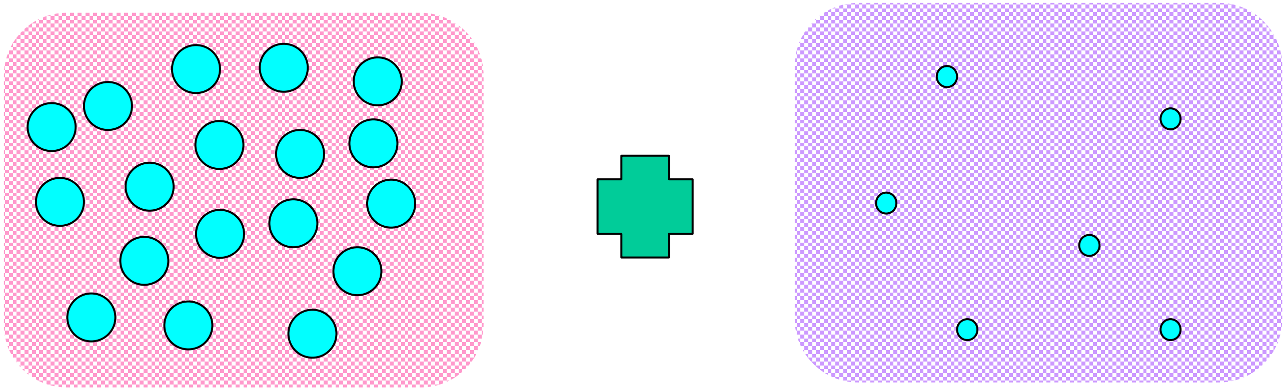
Objective

Toward further miniaturization of SNDs

We study effects of H_2 introduction to the SNDs growth in the pulsed SiH_4 supply to VHF Ar plasma system

Pulsed SiH_4 in Ar plasma

Pulsed H_2 in SiH_4 plasma



High deposition rate

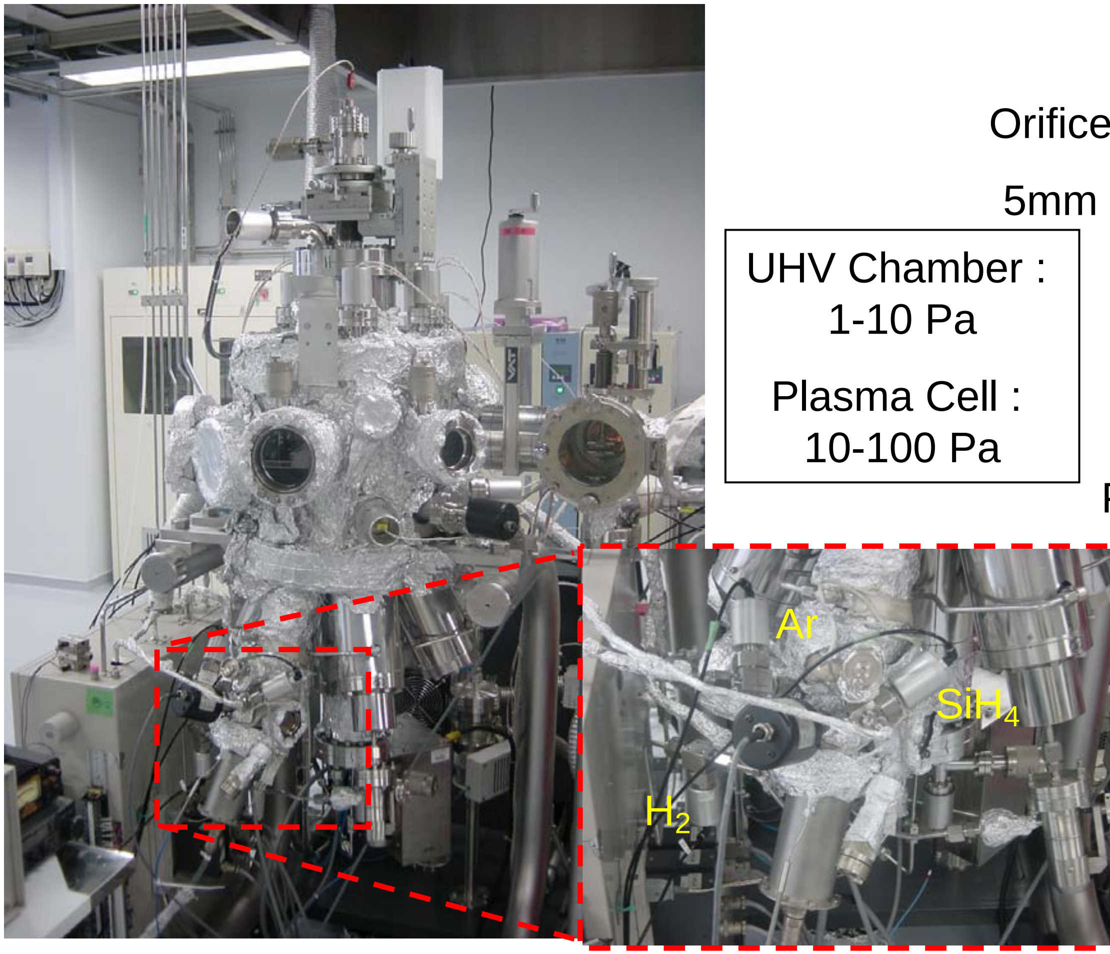
Mono-dispersed
with smaller diameter

Investigation of SND growth mechanism in $SiH_4/H_2/Ar$ chemistry

Experimental

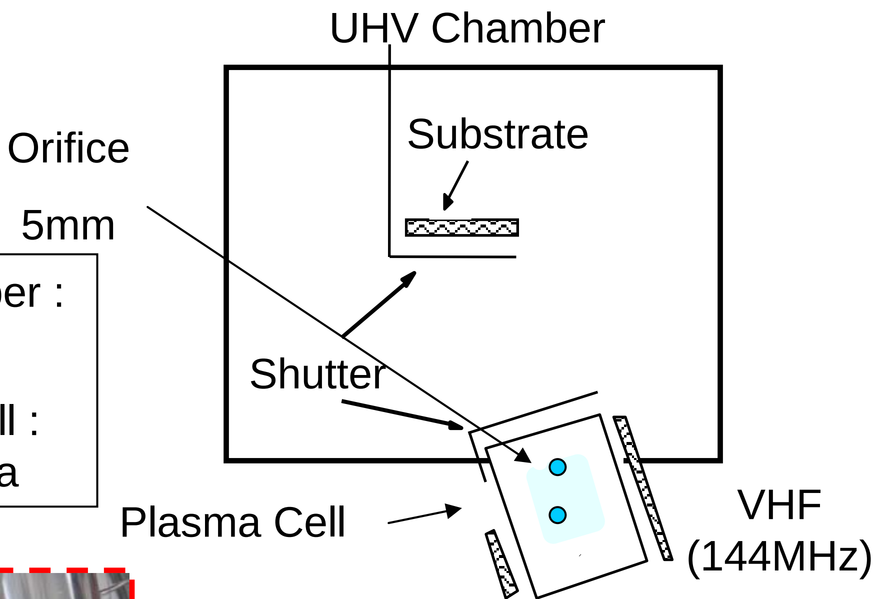
Apparatus

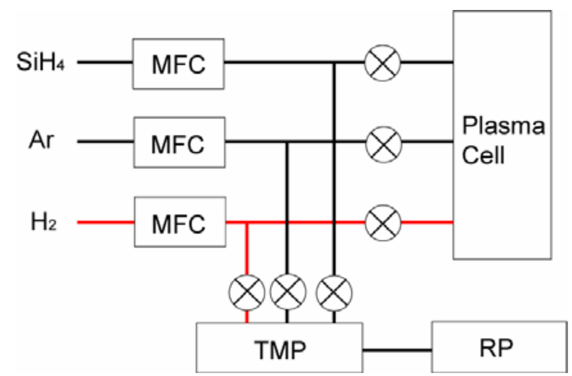
Newly introduced deposition chamber



UHV Chamber :
1-10 Pa

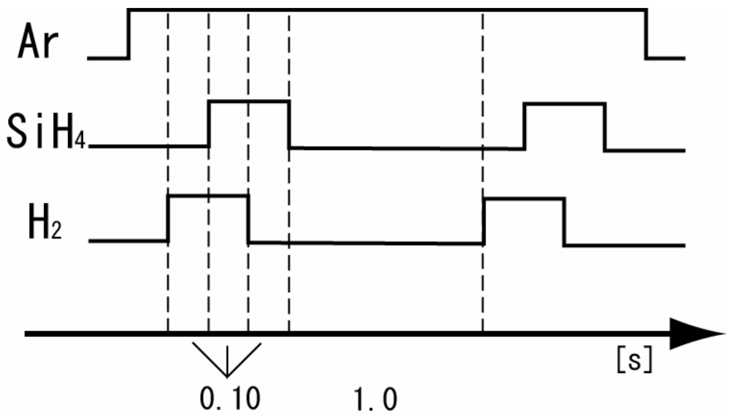
Plasma Cell :
10-100 Pa



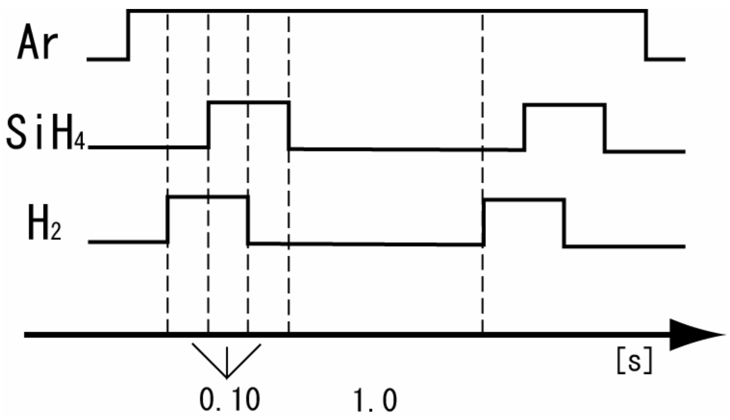


Gas supply conditions

Pulsed SiH_4 and Pulsed H_2 in Ar plasma



Pulsed SiH_4 in Ar/H_2 plasma

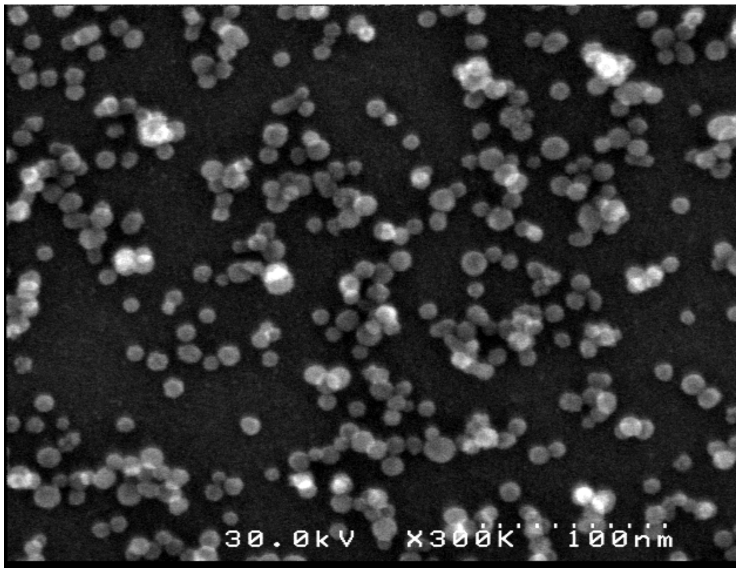


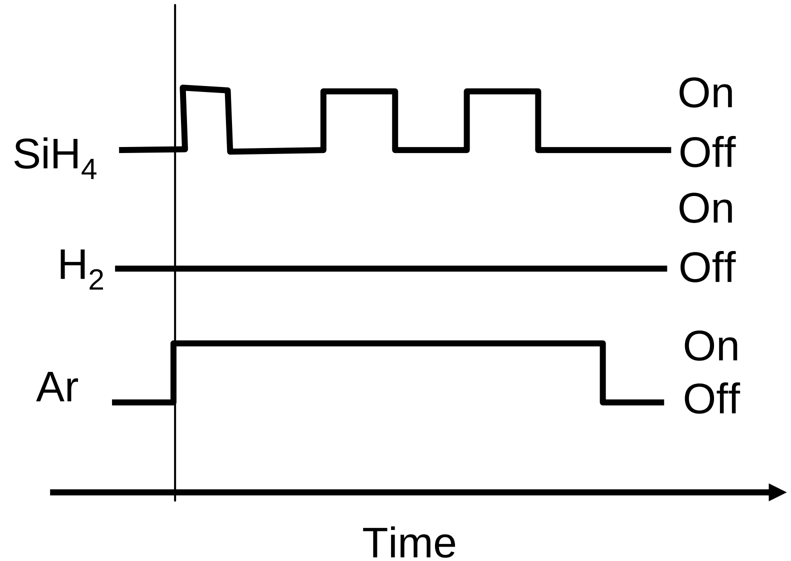
Observations

Shape, Size – SEM (Hitachi S-5000)
Crystal or Amorphous – TEM

Results

Pulsed SiH_4 supply to Ar plasma — w/o adding H_2





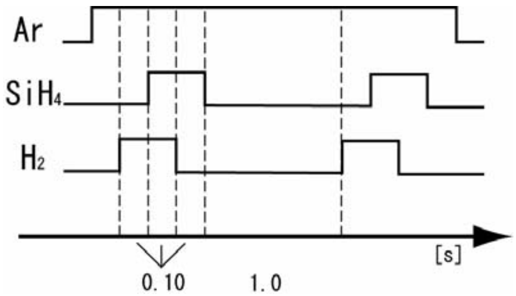
Spherical SNDs observed

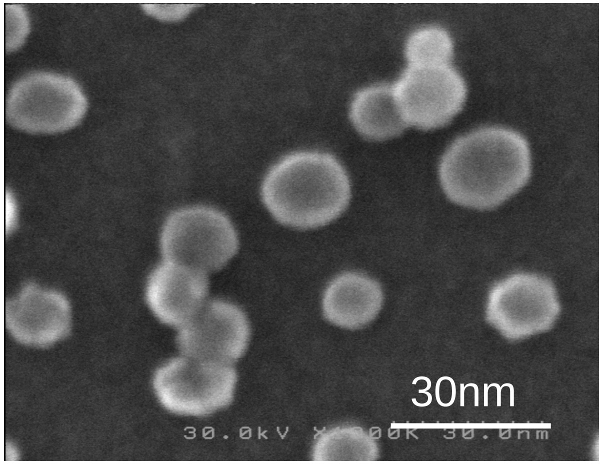
Single crystallized

Addition of Pulsed H_2 Supply

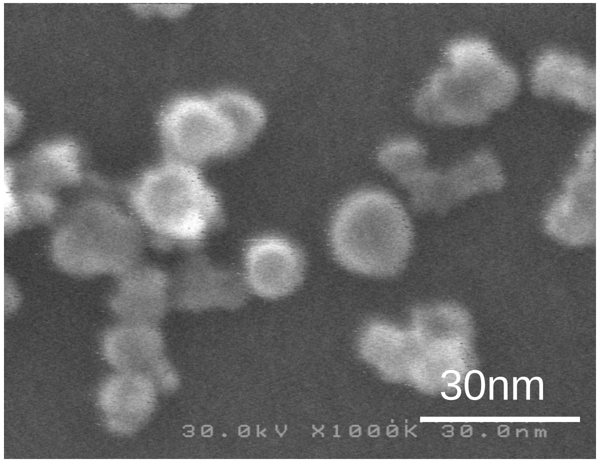
SEM images

SiH_4 1 sccm Ar 90 sccm

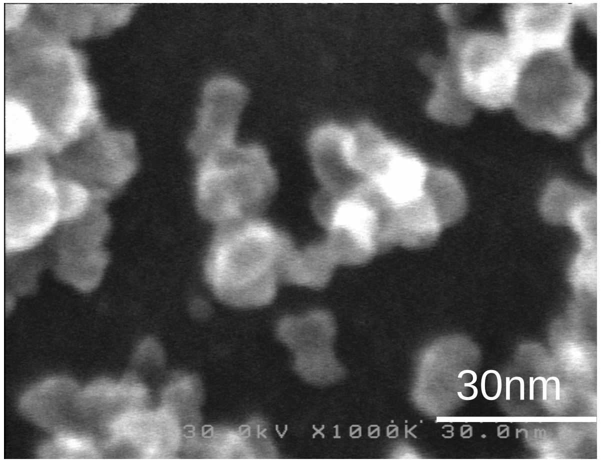




H_2 0.5 sccm



H_2 1 sccm



H_2 20 sccm

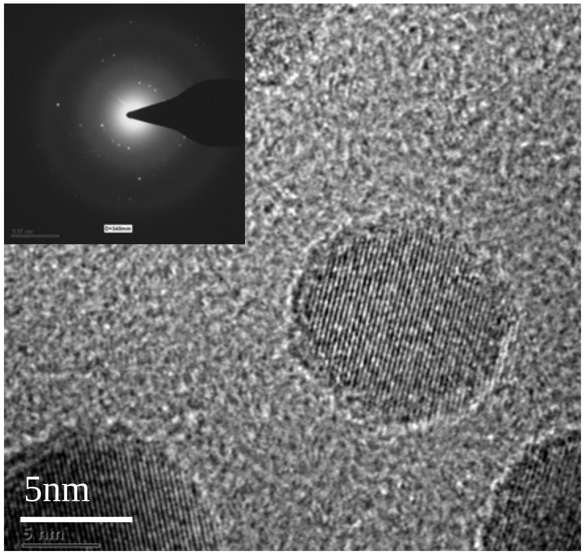
With increasing H_2 flow rate

→

- Number of aggregated clusters increases
- Size of individual dots tends to decrease

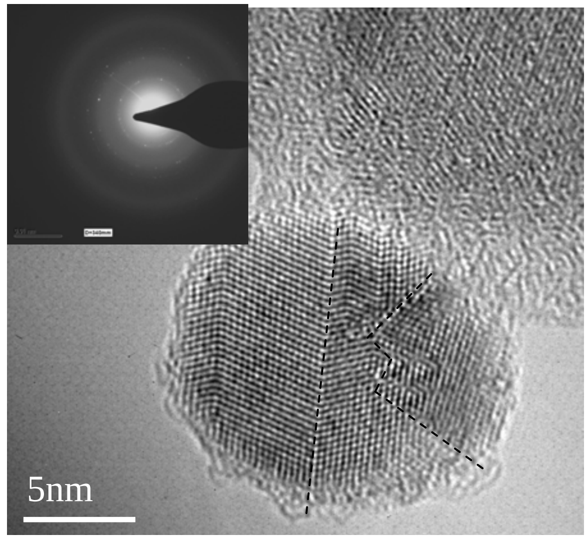
Addition of Pulsed H_2 Supply

—— TEM images



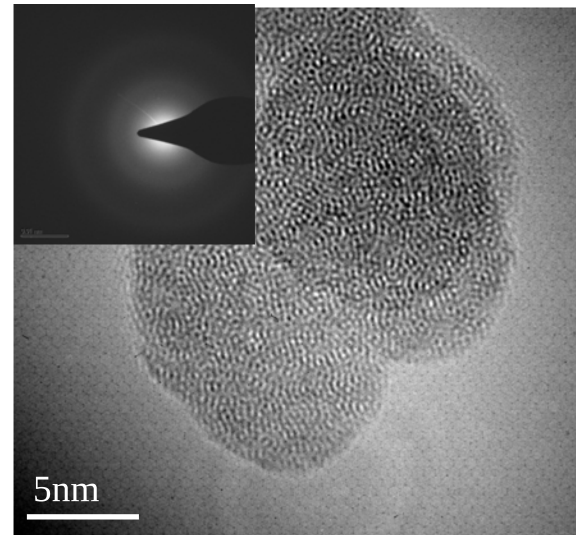
H_2 0.5 sccm

Single-crystalline



H_2 1 sccm

Poly-crystalline

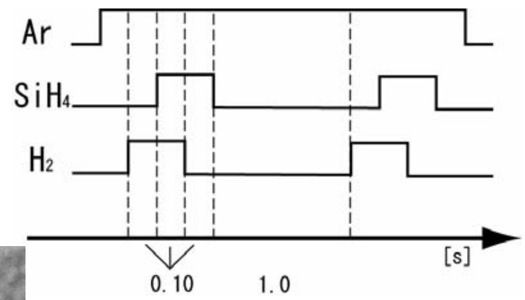


H_2 20 sccm

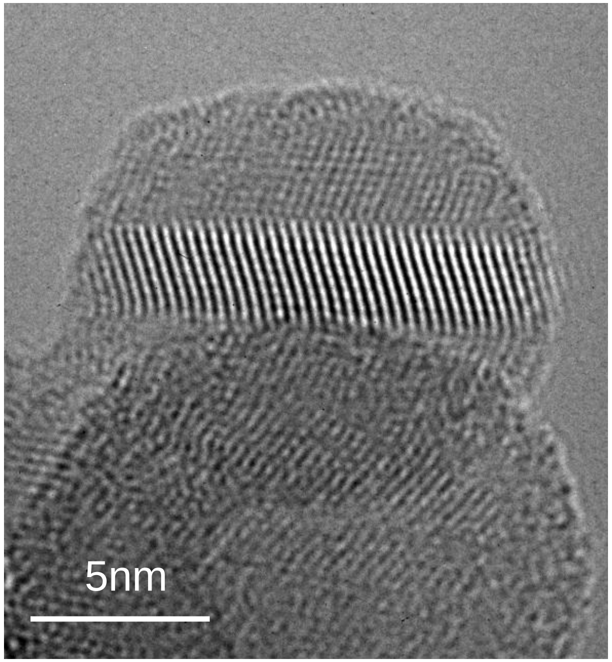
Amorphous

→ Crystallinity decreases with increasing H_2 flow rate

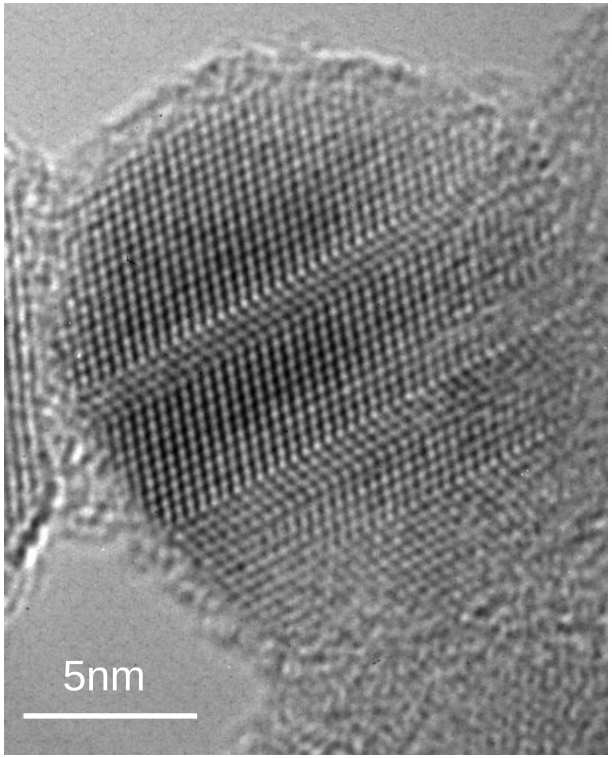
Different Ar flow rate



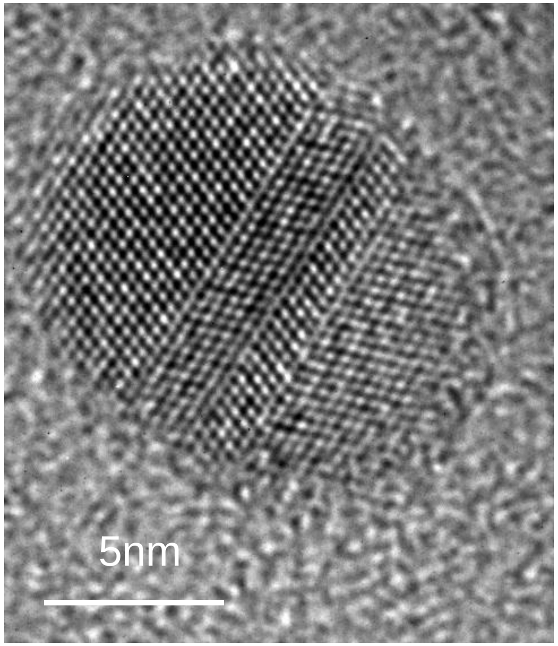
SiH_4 1 sccm H_2 1 sccm



Ar 30 sccm



Ar 45 sccm

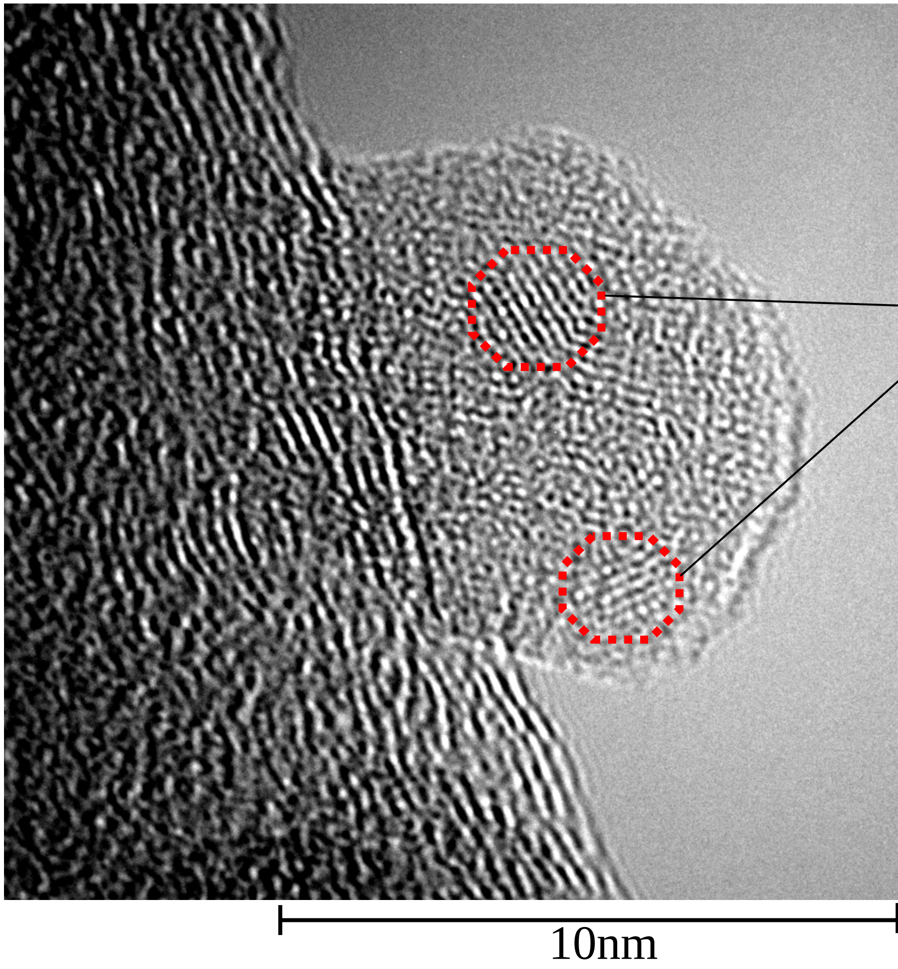


Ar 90 sccm

→ Change of Crystallinity is related to addition of H_2

Addition of H_2 to background Ar plasma

Pulsed SiH_4 in Ar/H_2 plasma



Multi-domain structure

Crystallization is likely to be blocked by adding H_2

Discussion

Effects of H_2 dilution

In Si thin film growth by PECVD using H_2/SiH_4

H_2 dilution induces change from amorphous to crystalline

N. Shibata *et al.,* Mat. Res. Soc. Symp. Proc. **95,** 225 (1987).

Production of Si nano-particle using VHF discharges

High H_2/SiH_4 ratio causes better crystallinity

M. Shiratani *et al.,* Trans. Mat. Res. Soc. Jpn. **30,** 307 (2005).

Our results has opposite tendency

Effects of H_2 addition are different in our condition using $SiH_4/Ar/H_2$ chemistry?

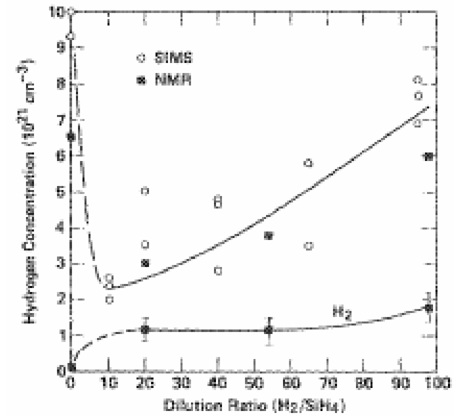
Possible model

Excess H_2 incorporation

In microcrystalline Si deposition

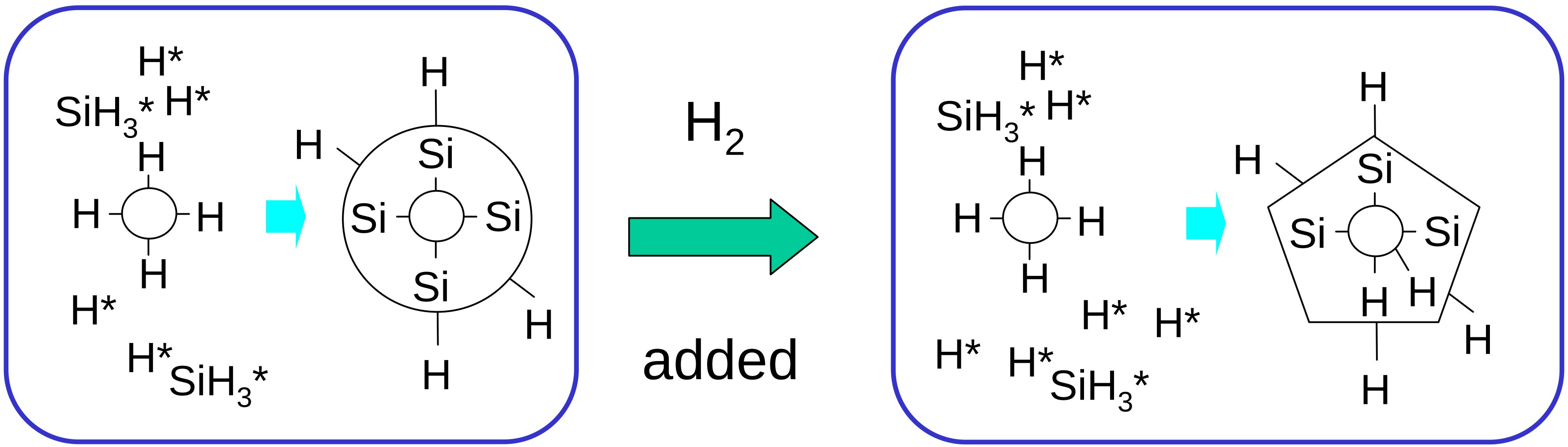
H_2 is incorporated at highly diluted condition

N. M. Johnson *et al*., Appl. Phys. Lett. **53**, 1626 (1988).



High SND growth rate in Ar plasma

→ Excess H_2 easily incorporated



Sufficient H_2 for crystallization

Amorphous phase

Why does it happen?

High deposition rate in pulsed SiH_4 supply to Ar plasma

→ Due to matching effect between ionization energy of SiH_4 and Metastable state in Ar

Current condition w/o H_2 actually realized high deposition rate with good crystallinity

→ Might has a tendency to change drastically by slight change of parameter

Quantitative analysis of H_2 incorporation is important.

Are SNDs miniaturized?

Actually size of individual SNDs was reduced.
Preventing aggregation is future issue.

Summary

We studied SND formation in the pulsed-gas VHF plasma process combined with three gas sources of SiH_4, Ar, and H_2.

We found that the crystallinity of individual dots changed drastically by adding H_2 into SiH_4/Ar system

Observed effects of H_2 addition has opposite tendency compared with previous reports, and might be explained as a unique features in our SiH_4/Ar/H_2 system.

Size reduction of individual SNDs by adding H_2 is useful for future SND applications.

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