Experimental analysis on material removal mechanism in CMP process for SiO_2 film with AFM observation

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Kyutech

Kyushu Institute of Technology

History

1909	Founded in 1909 as Meiji College of Technology (4-year, private)
1921	Became 4-year national institution
1949	Under the national school establishment law, Meiji College of Technology was renamed Kyushu Institute of Technology.
1986	Faculty of Computer Science and Systems Engineering was established.
2000	Graduate School of Life Science and Systems Engineering (Independent postgraduate school) was established.
2004	All National Universities transformed into National University Corporations; Kyushu Institute of Technology was also incorporated as a National University Corporation.

Dr. Kenjiro Yamakawa
First President

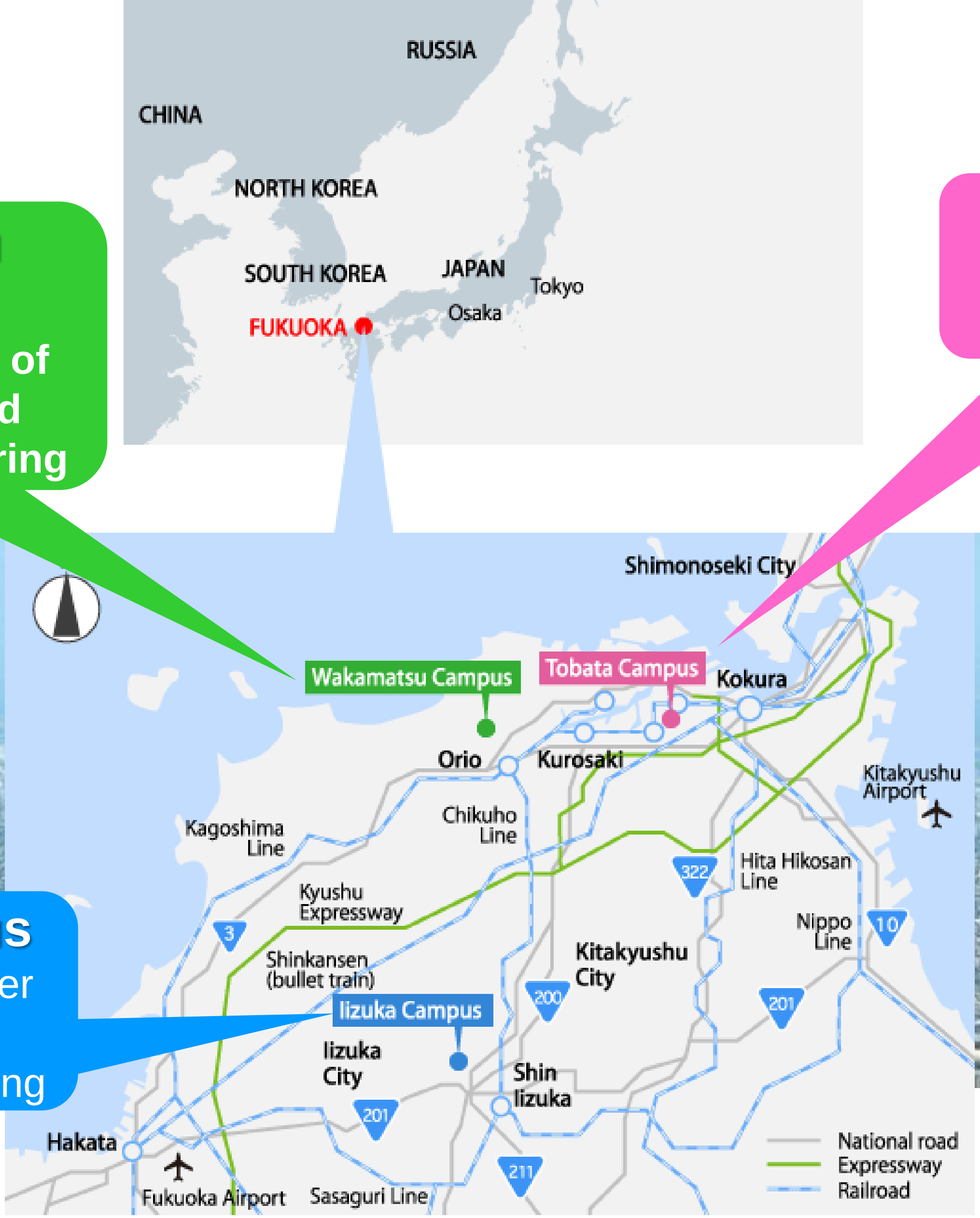
Keiichiro Yasukawa
Founder

Locations of Kyutech Campuses

Wakamatsu Campus
Graduate School of Life Science and Systems Engineering

Tobata Campus
School of Engineering

Iizuka Campus
School of Computer Science and Systems Engineering



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History of Polishing Mechanism Study

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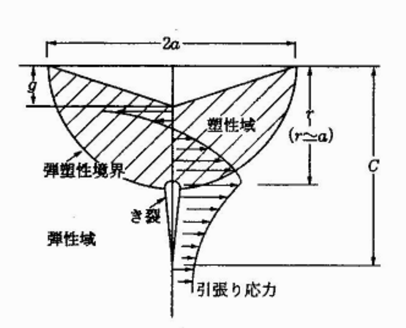
☐ 3 theories on material removal mechanism in polishing as follows :

(1) Theory of Micro Cutting

Material removal with destruction by forcing abrasive grains into material

metal : plastic deformation

ceramics : cracks generation as Hertz crack



(2) Theory of surface flow（Bowden, Tabor ）

Heat generation at contact point → high temperature softening, melting → surface flow → formation of Beilby layer

F.P. Bowden, D. Tabor : Tha Friction and Lubrication of Solids, Oxford (1954)

(3) Theory of chemical reaction

Grebenschikov ：soft gel layer on glass surface

V. Grebenschikov : Keram, I Stekro, 7 [11/12] (1931)

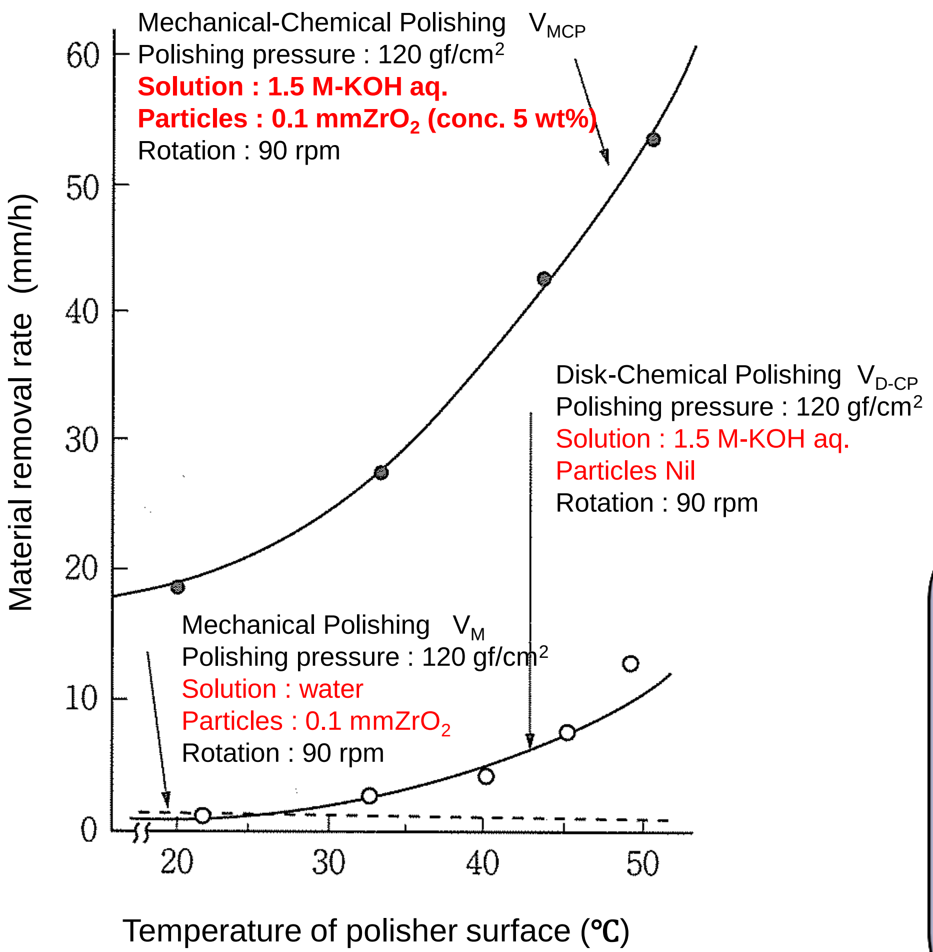
Kaller ：chemical reaction among glass/polisher/polishing liquid/particles

A. Kaller : Neuere Erkenntnisse uber die Vorgange beim Polieren des Glases, Mschr. Feinmech. Opt. 79 (1962) 5

Izumitani ：property of hydration layer determines polishing ability

T. Izumitani : Treatise on Material Science & Technology, vol. 17, Academic Press, New York (1979)

Basic work of chemical elements and fine particles in slurry



Si single-crystal polishing

Toshiro Doi : Optical Technology Contact, 31 [10] (1993) 47

Chemical elements
+
Fine particles
⇩
Activation in Polishing

Slurry's function

chemical elements :
chemical reacted layer formation

fine particles :
unidentified, but significant

Material removal model with fine particles in slurry

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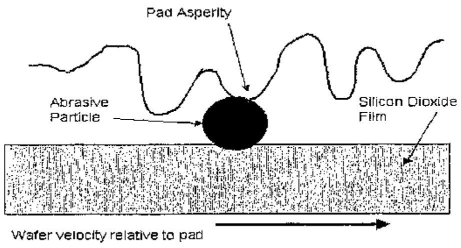
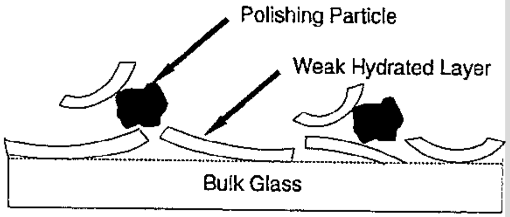
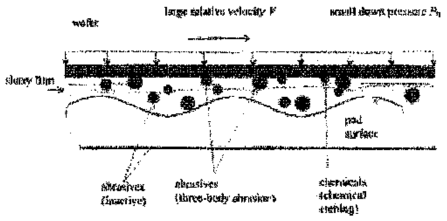
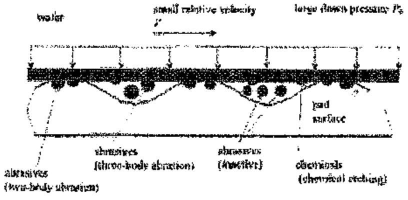






(a)

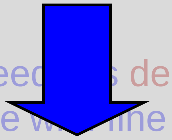


(b)

M
W

Material removal proceeds as mechanical cutting process with fine particles with backup of polishing pad

M
E



Material removal process procee s destruction and flaking of hydration layer on wafer surface w ine particles in slurry

N.B. Kirk, J. Wood : Glass polishing,
E

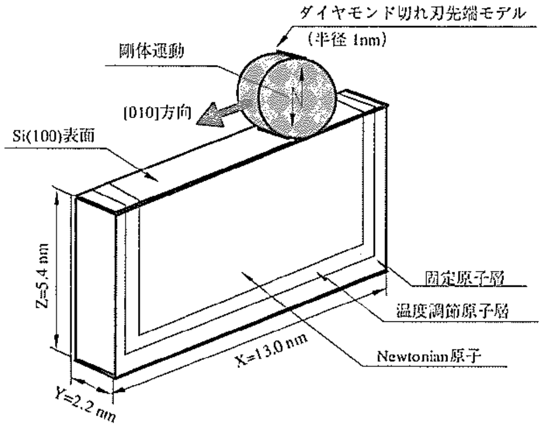
Is it realistic phenomena ?

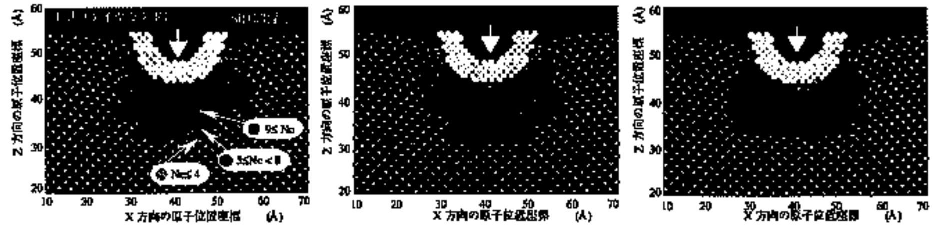
M
W

Material removal with fine particles is the essential function !

J. Luo, D. A. Dornfeld : Material Removal Mechanism in Chemical Mechanical Polishing : Theory and Modeling, IEEE Transactions on Semiconductor Manufacturing, Vol. 14, No.2 (2001) pp112-133

Material removal mechanism based on Molecular dynamics

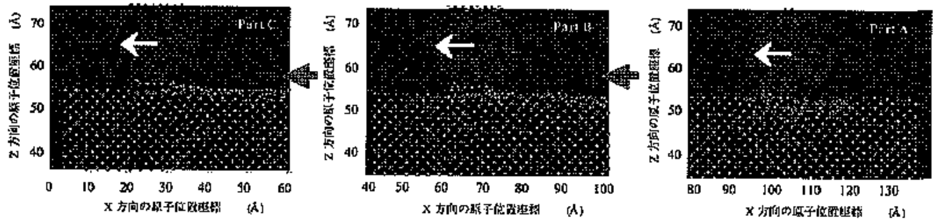




(a) 工具降下速度250m/sの場合の原子挙動

(b) 工具降下速度5m/sの場合の原子挙動

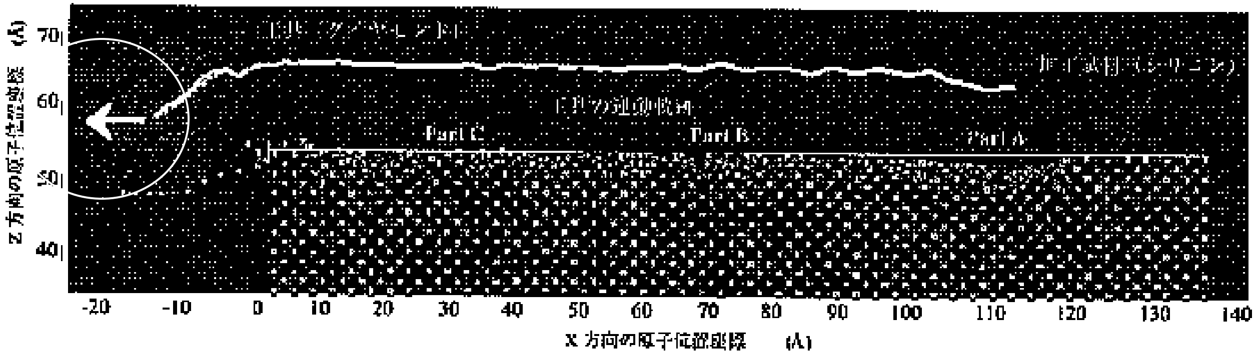
(c) 速度補正を施した見かけの工具降下速度250m/s



(d) 工具移動距離8.0nm（Part C）での加工作用：表面原子層の配列をアモルファス化するが除去効果はない．

(c) 工具移動距離4.0nm（Part B）での加工作用：工具表面にSi原子が付着した状態で負の切り込みとなる．

(b) 工具移動距離0.8nm（Part A）での加工作用：工具表面にSi原子が付着し１原子層程度が除去される．

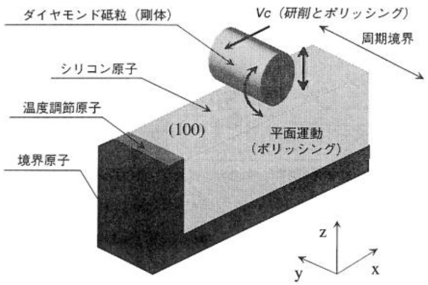


(a)　１回の工具運動と加工試料表面原子層の状態（制御温度293K）

Y. Takaya, K. Kimura : Analysis on phenomena of optical radiation pressure micro-machining with molecular dynamics, J. of JSAT, 47,12 (2003) 677-683

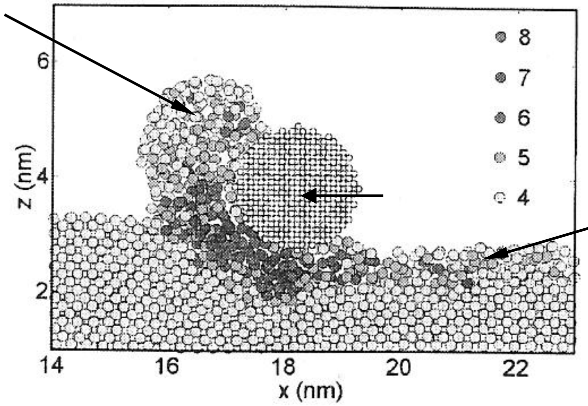
高谷裕浩、木村景一：分子動力学による光放射圧マイクロ加工現象の解析、砥粒加工学会誌、47,12 (2003) 677-683

Material removal mechanism based on Molecular dynamics



Initial model on molecular dynamics simulation

chip by plastic flow with a-Si,
without dislocation

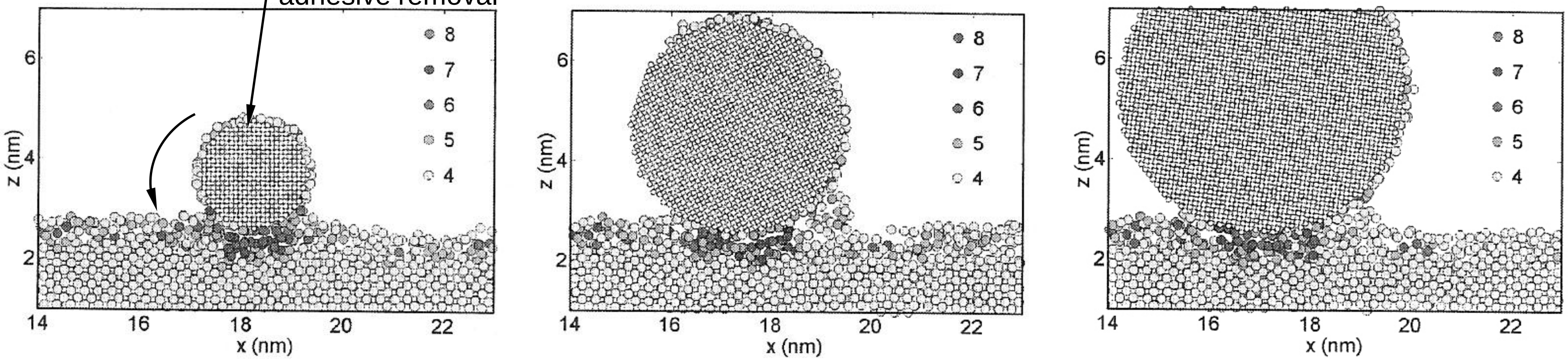


R =1.07 nm
V = 200 m/s
d = 0.69 nm

a-Si layer

(a) Grinding (R=1.07nm)

adhesive removal



(b) Polishing (R=1.07nm) **(c) Polishing (R=2.14nm)** **(d) Polishing (R=2.85nm)**

Damaged layer on single crystal Silicon after grinding and polishing

- H. Tanaka, S. Shimada, N. Ikawa : Prediction of an ideal surface processing of monocrystalline silicon for minimal surface roughness and damage by molecular dynamics analysis, J. Soc. Grinding Engineers, 45, 4 (2001) 175-180 (in Japanese)

田中宏明，島田尚一，井川直哉：分子動力学シミュレーションによる単結晶シリコン理想表面生成プロセスの予測，砥粒加工学会誌 Vol.45, No.4 (2001) pp.175-180

Material removal mechanism based on Molecular dynamics

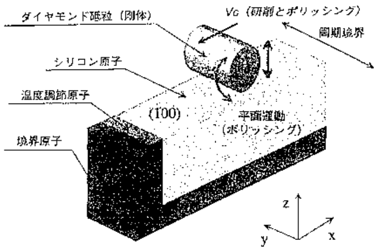
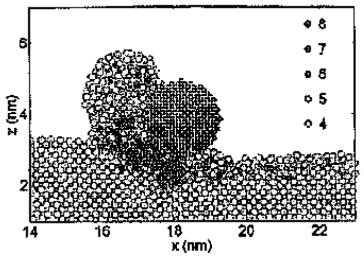
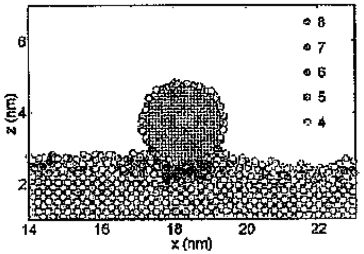


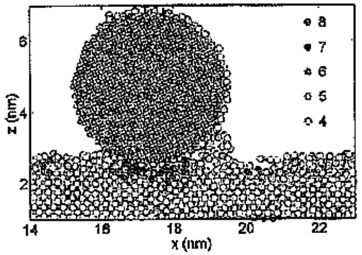
図1　分子動力学シミュレーションによる初期モデル



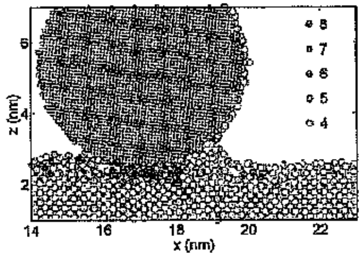
(a) 研削 (R=1.07nm)



(b) ポリッシング (R=1.07nm)



(c) ポリッシング (R=2.14nm)



(d) ポリッシング (R=2.85nm)

1. Particles' slide on the surface
   - micro cutting
   - amorphous layer formation

2. Atomic bonding force in amorphous layer is weak

3. Atoms in amorphous layer with weak bonding force adhere on contacting and rolling particles

4. Material removal proceeds continuously

- H. Tanaka, S. Shimada, N. Ikawa : Prediction of an ideal surface processing of monocrystalline silicon for minimal surface roughness and damage by molecular dynamics analysis, J. Soc. Grinding Engineers, 45, 4 (2001) 175-180 (in Japanese)

田中宏明，島田尚一，井川直哉：分子動力学シミュレーションによる単結晶シリコン理想表面生成プロセスの予測，砥粒加工学会誌 Vol.45, No.4 (2001) pp.175-180

Tips : conventional material removal model

1. Chemical elements in slurry forms chemical reacted layer on the wafer surface

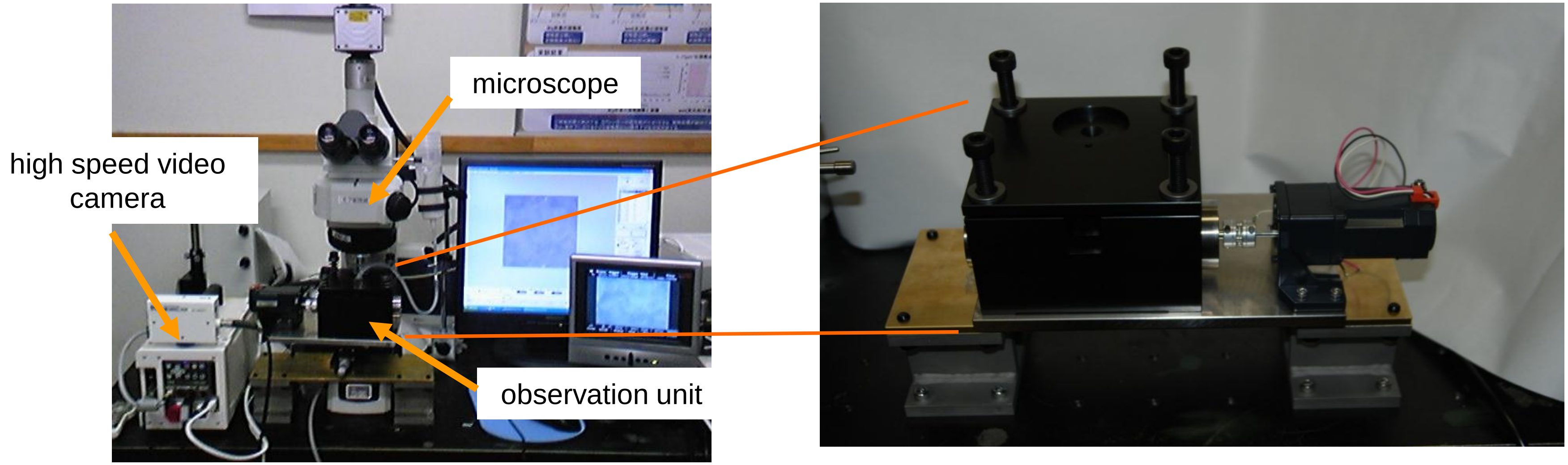
2. Two suppositions for slurry particles' function as follows :

(1) micro cutting by embedded particles on the wafer surface

(2) chemical adhesion by slurry particles

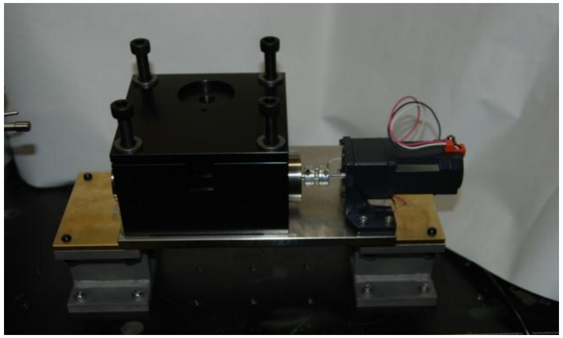
At first, contact area observation between polishing pad and wafer is attempted.

Dynamic observation unit for contact area



microscope	Nikon	Industrial microscope LV150
Halogen lamp	Nikon	LV-KH50PC
Anti-reflective film	Nichiyu	ReaLook 7802UV
High speed video camera	Nack Image Technology	MEMRECAM fx RX-6G 2000 fps

Dynamic observation unit for contact area



Observation unit

contact glass plate and pad

glass plate is fixed
Pad is rotating

supply D.I. water at center

observe contact area

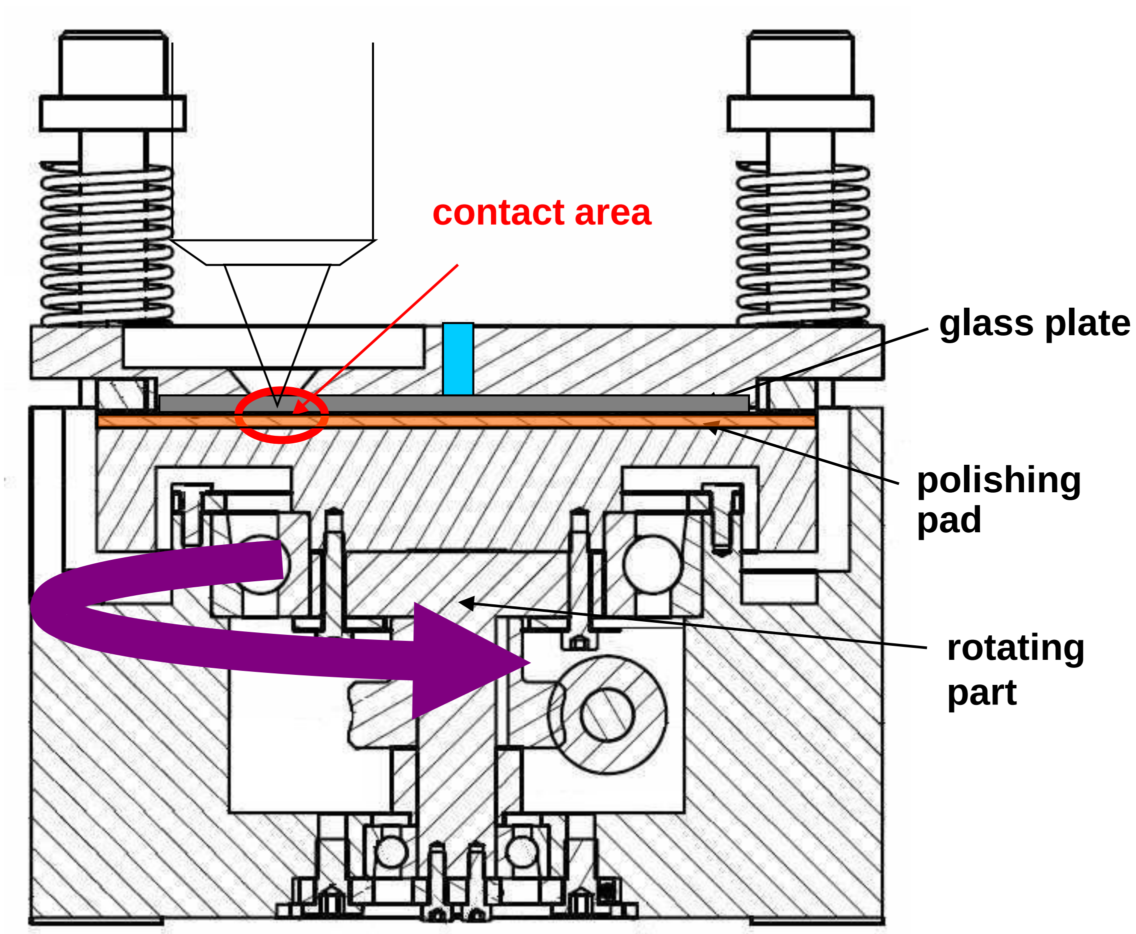
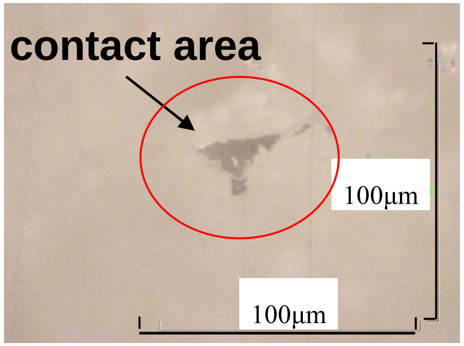


Image recognition method

dry observation

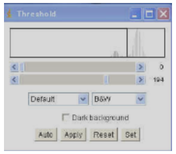


bright area :
no-contact area

dark area :
contact area

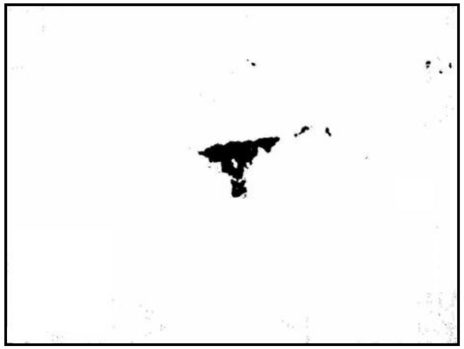
X 20

binarization

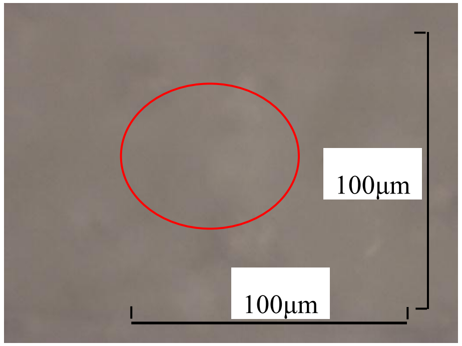


0
194
Default
B&W
☐ Dark background

processed image

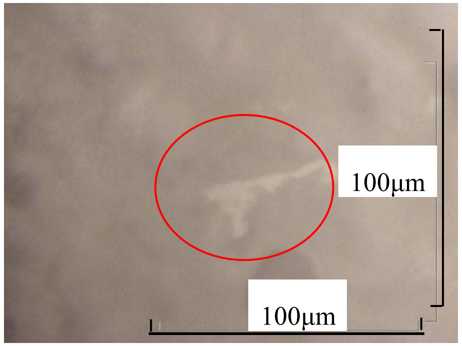


wet observation



hard
recognition

with anti-reflection film



bright area :
contact area

dark area :
no-contact area

Dynamic Contact between polishing pad and wafer

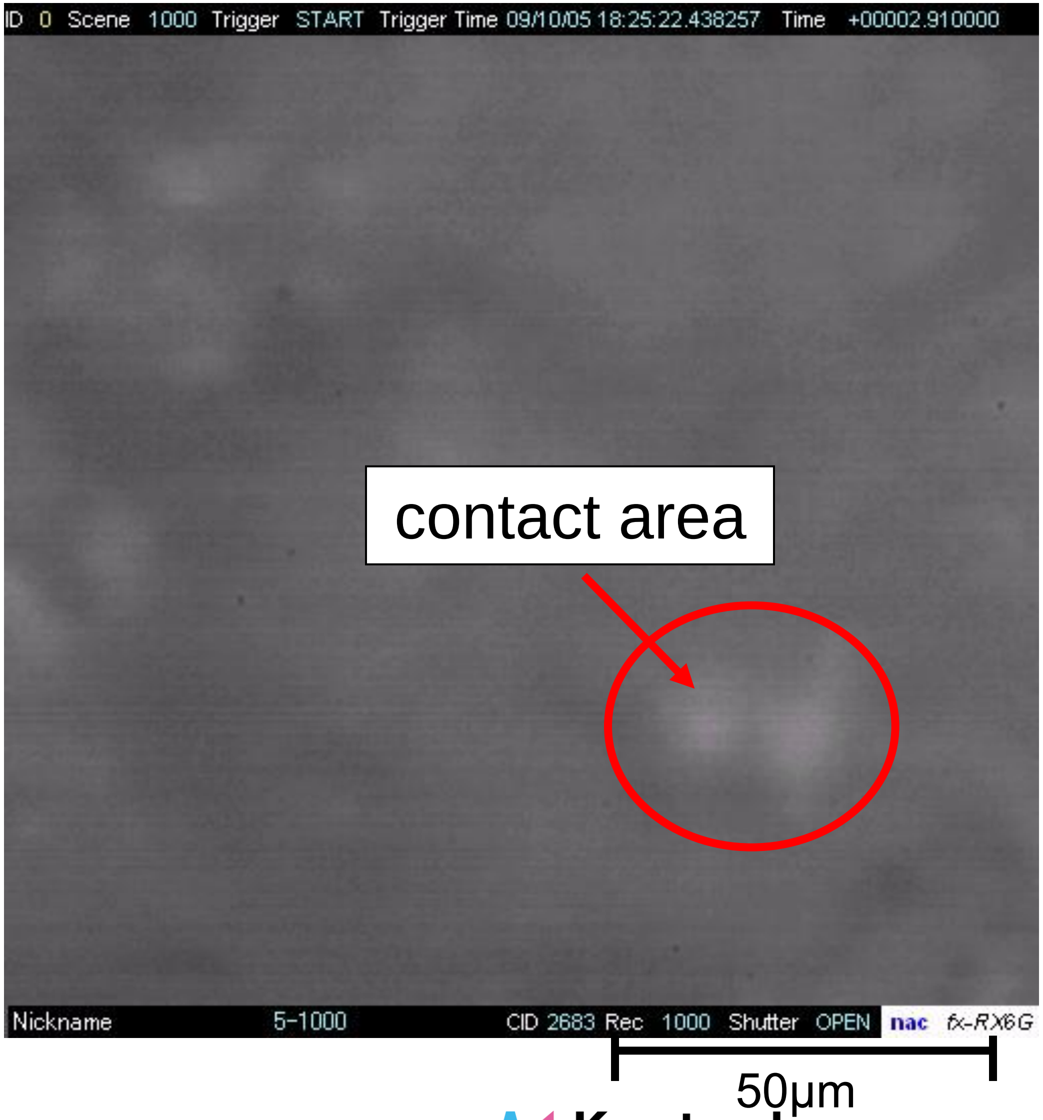
Contact area was taken as a movie with High speed video camera

[example]

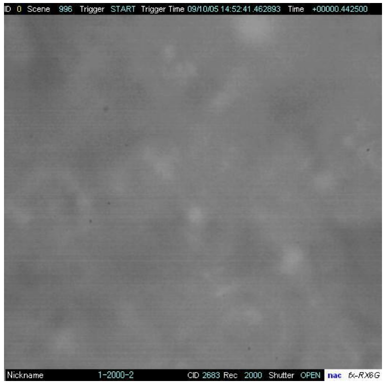
conditioner : #100
rotation : 0.95 min^{-1}
pressure : 3 psi
playback speed : 0.1 times

bright area : contact area

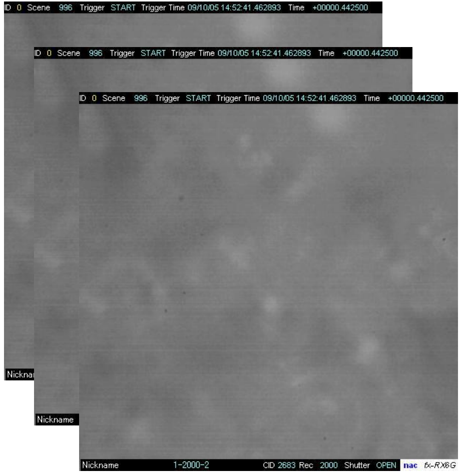
dark area : no-contact area



Calculations for “contact area ratio”

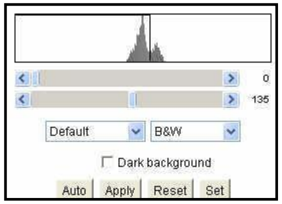


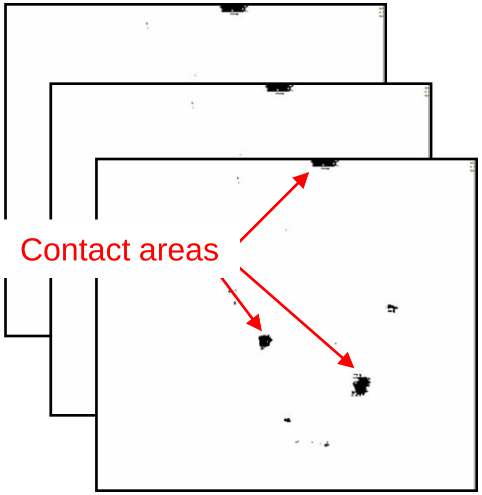
movie



still images

binarization


0
135
Default
B&W
☐ Dark background



after processing

$$\text{contact area ratio} = \frac{\text{contact area}}{\text{whole area of photograph}}$$

Influence by pressure variation

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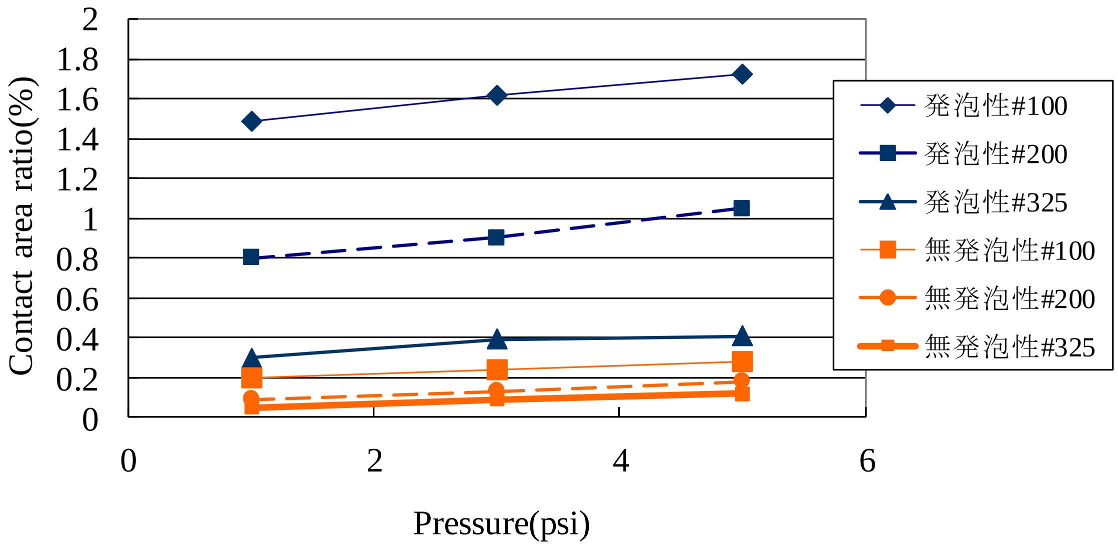
Calculations for “contact area ratio” with pressure variation

(1) Observed contact areas with 6 kinds of conditioned polishing pad
(2) Selected 10 Images at random and calculated “contact area ratio”



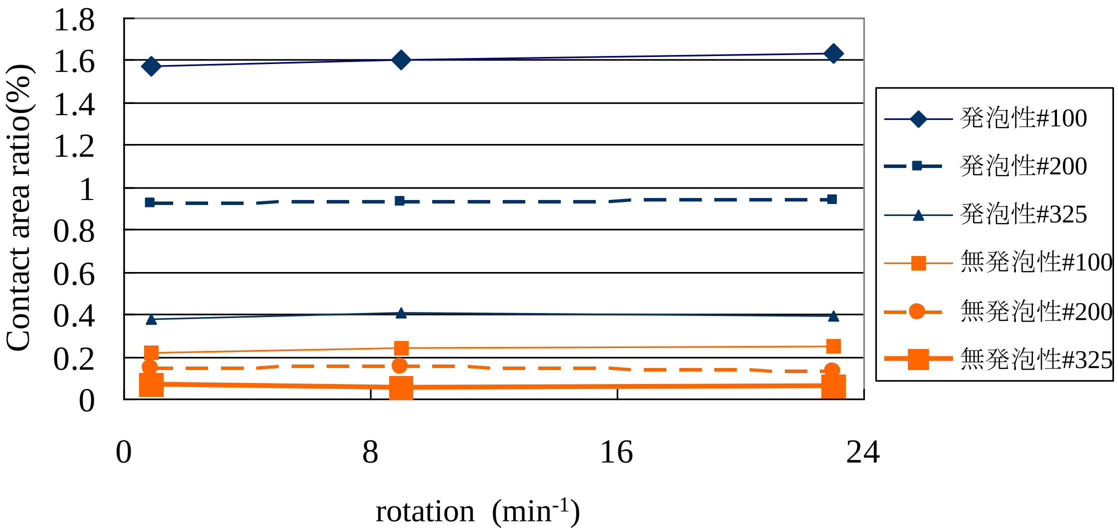
- polishing pad :
  IC1000 , no foaming type
- conditioner :
  #100, #200, #325
- Pressure : 1, 3, 5 psi
- rotation : 9.5 min-1

1. Contact area ratio increases with pressure growing
2. Contact area ratio of foaming type polishing pad is larger than that of no-foaming pad

Influence by polishing pad rotation

Calculations for “contact area ratio” with rotation speed variation

(1) Observed contact areas with 6 kinds of conditioned polishing pad
(2) Selected 10 images at random and calculated “contact area ratio”



- polishing pad :
  IC1000 , no foaming type
- conditioner :
  #100, #200, #325
- Pressure : 3 psi
- rotation : 0.9, 9.5, 23.5 min-1

1. Contact area ratio has nothing to do with polishing pad rotation speed
2. Contact area ratio is less than 2 % in every normal conditions

Tips : conventional material removal model

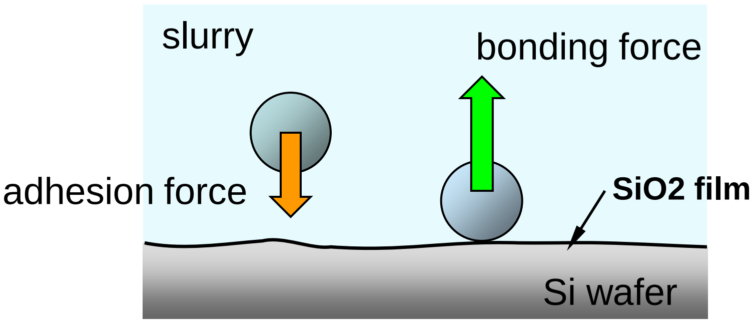
1. Contact area observation between rotating polishing pad and glass plate was attempted.

2. Contact area ratio between polishing pad and wafer is extremely small, less than 2 %.

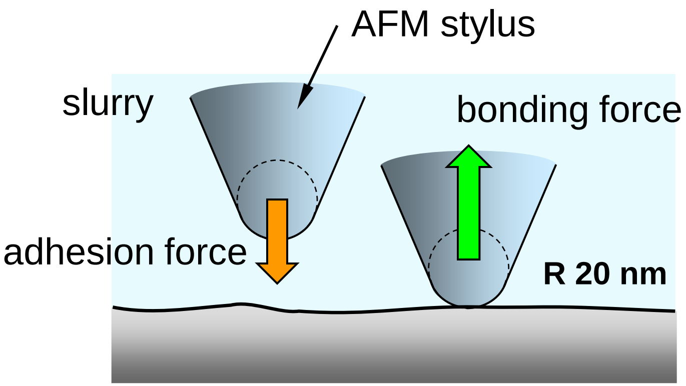
3. It is difficult to consider that material removal happens at the contact area with scratching by slurry particles.

As a second step, the possibility of particle's adhesion is investigated with AFM.

Force measurement between wafer and particles in slurry



forces applying particle

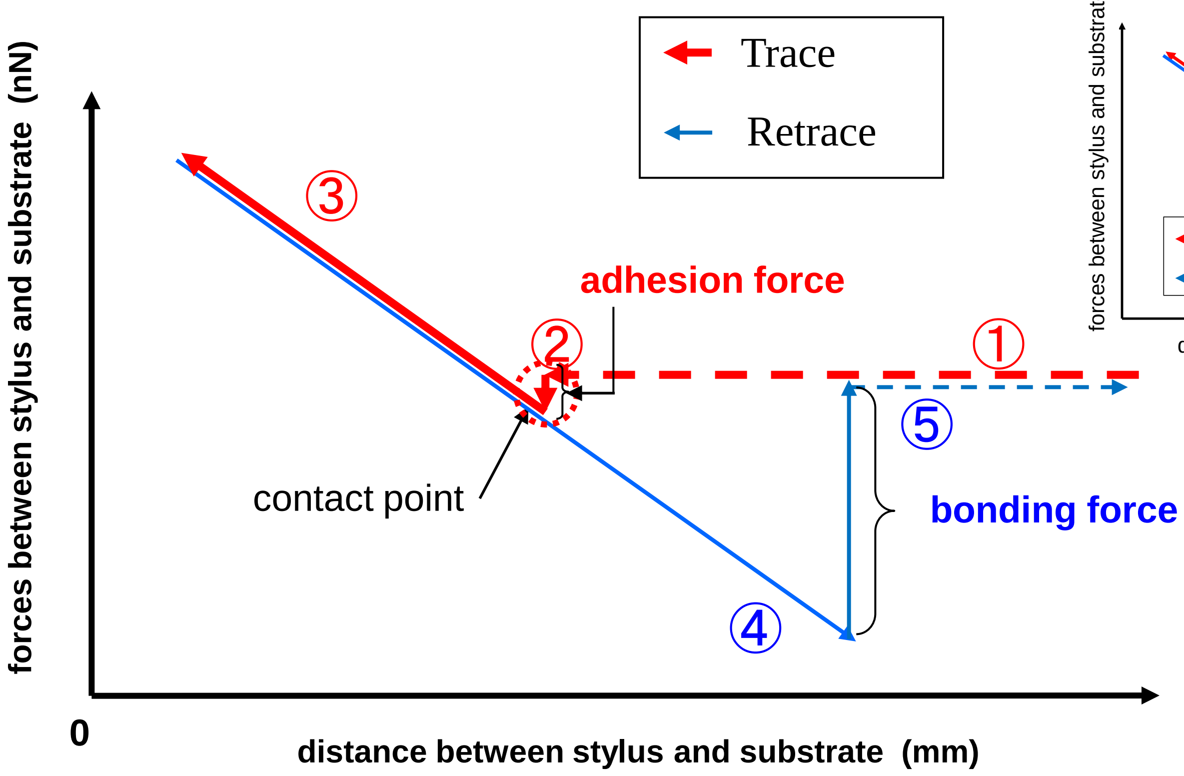


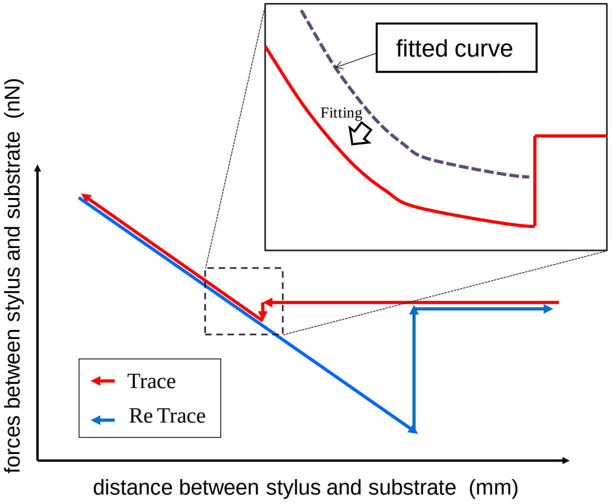
forces applying stylus

MFP-3D (Asylum Research)

AFM	**MFP-3D (Asylum Research)**
stylus	**SiO_2**
substrate	**Si with SiO_2 film**
solution	**H_2O, H_2O+NH_4OH**

Force curve measurement



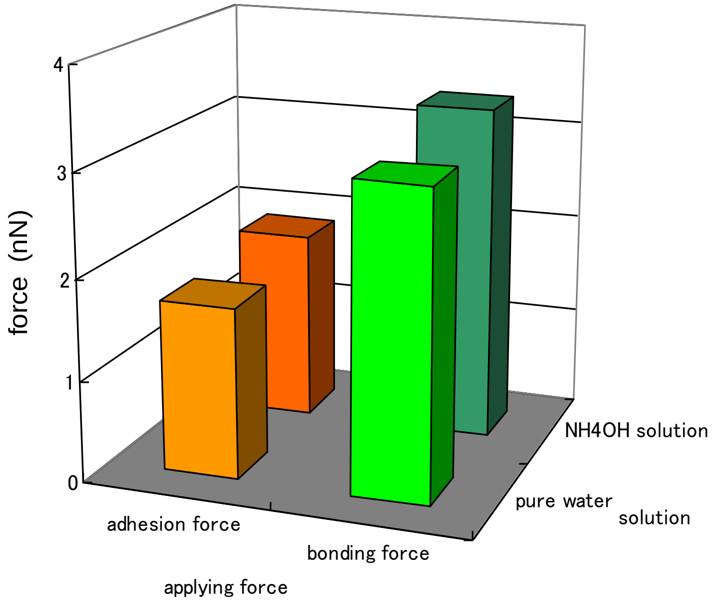


Fitting equation

$$F = \frac{4}{3}\frac{E\sqrt{R}}{1-\nu^2}\delta^{3/2}$$

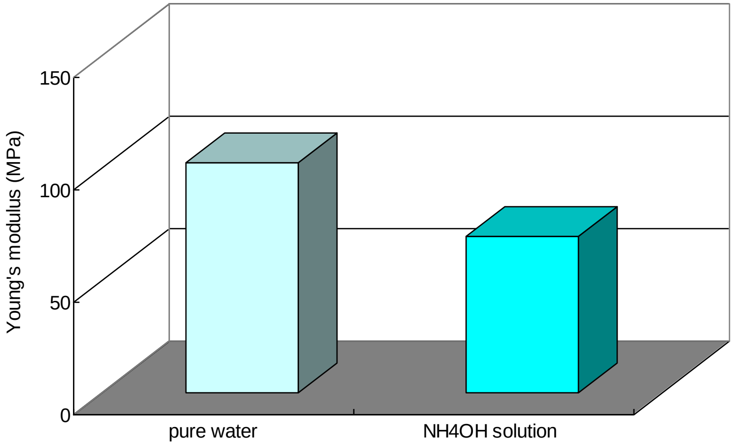
F : load [N]
d : strain [m]
E : Young's ratio [N/m^2]
n : Poisson ratio（0.5）
R : Radius at tip of stylus [m]

Applying forces between wafer and stylus



Adhesion forces and bonding forces between stylus and substrate

☑ SiO_2 wafer's Young's modulus in air : 50-90 GPa



Young's modulus of wafer surface in slurry

Substrate : Si wafer + SiO_2 film
Stylus : Si + SiO_2 coated

1. **Adhesion force and bonding force applies stylus tip**
2. **Bonding force is about 80% larger than adhesion force , and these are larger in NH_4OH solution than in water**
3. **Surface of SiO_2 wafer in NH_4OH solution becomes much softer than in water**

Observation of adhesion on stylus tip

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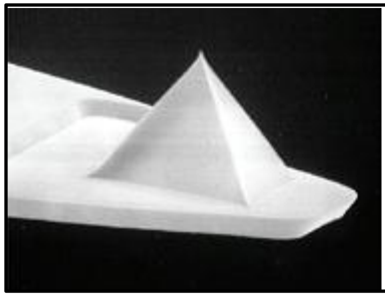
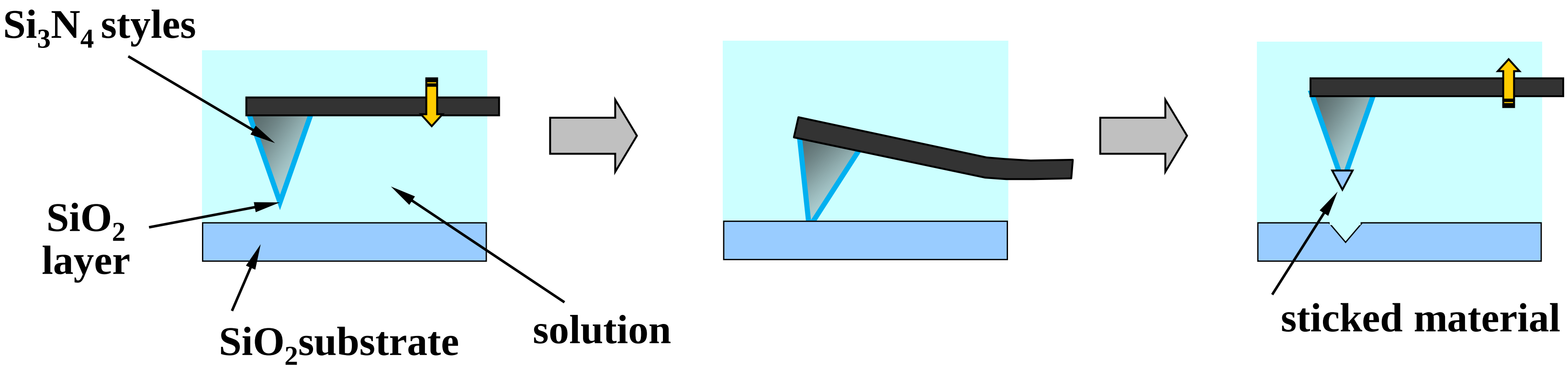
NanoscopeⅢa
Digital Instrments



DNP-S(Veeco)
OMCLTR800PSA(OLYMPUS)
Si_3N_4 (thermal oxidation on tip)
Radius of tip ：10～40 nm

Test piece	solution	measurement
SiO_2 wafer with thermal oxidation layer	D. I. water pH8.5(KOH,NH_4OH) pH10(KOH,NH_4OH)	SEM observation



Observed stylus tip with SEM

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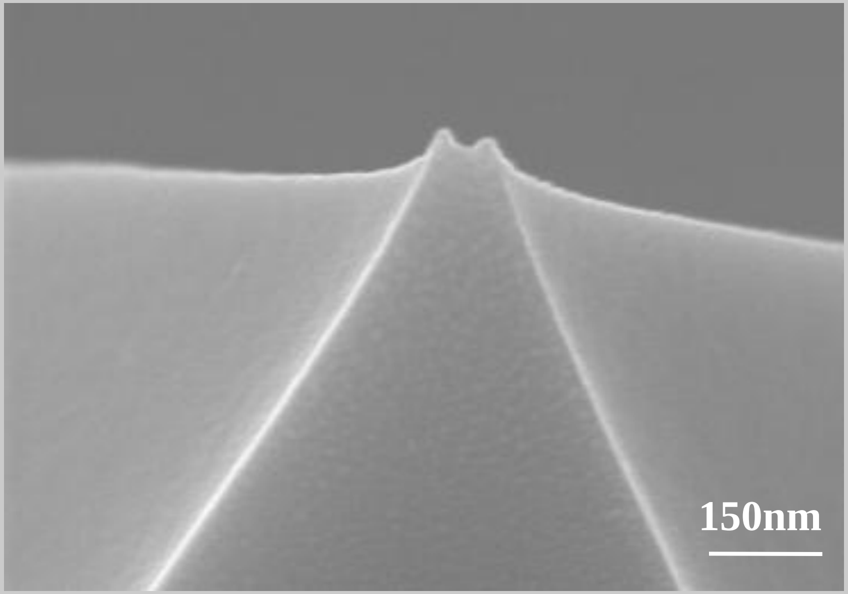
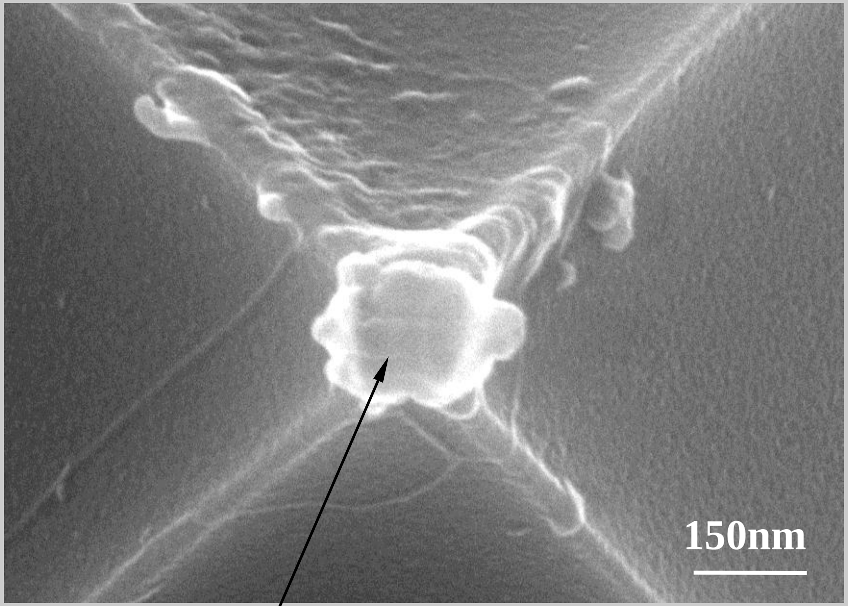
Before indentation



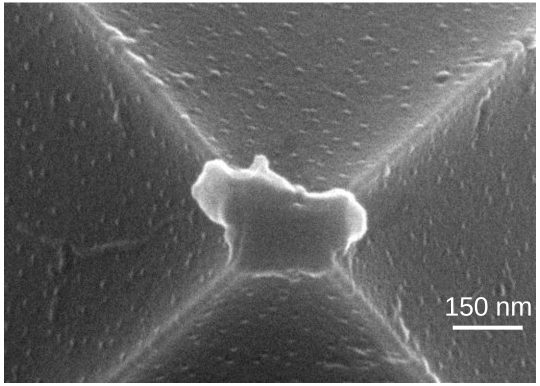
After indentation (pH7)



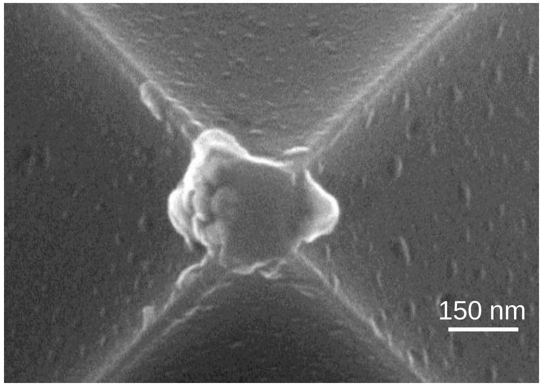
sticking material

Observed stylus tip with SEM

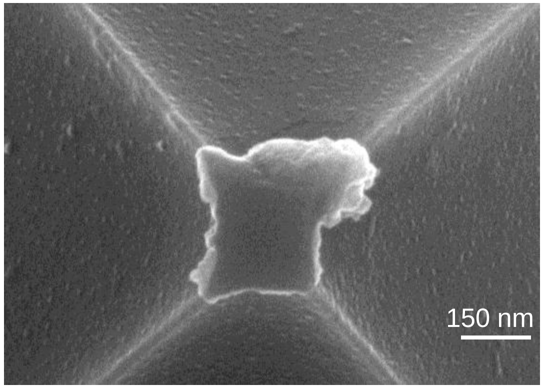
pH 8.5 / KOH



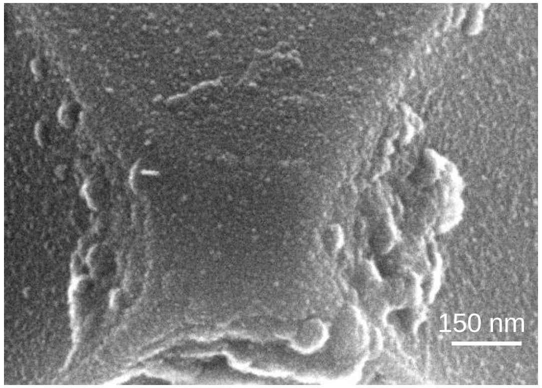
pH 8.5 / NH_4OH



pH 10 / KOH

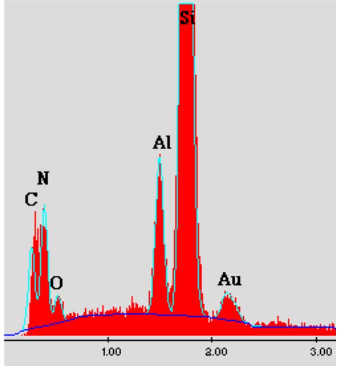


pH 10 / NH_4OH

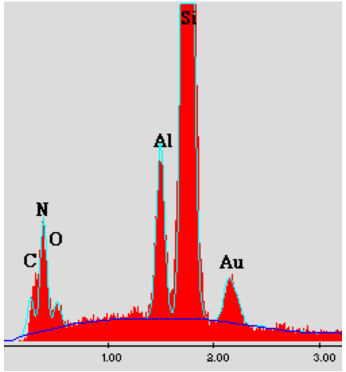


Analysis sticking material with EDX

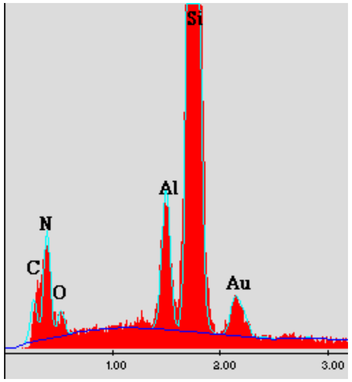
May 11, 2011



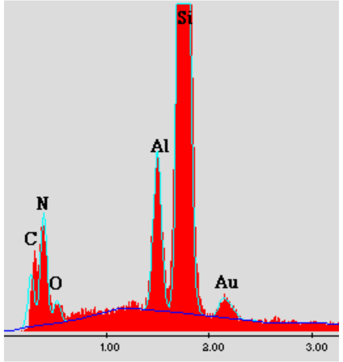
(a) unused



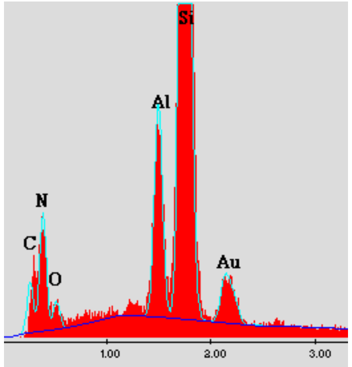
(c) pH8.5 (KOH)



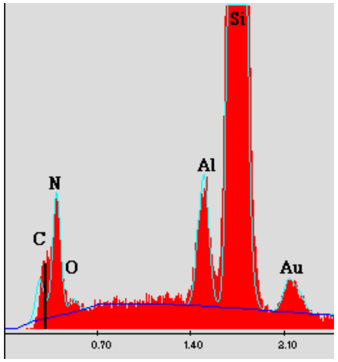
(e) pH10 (KOH)



(b)pH7(PureWater)



(d)pH8.5(NH_4OH)



(f) pH10 (NH_4OH)

Sticking material is “SiOx”

Tips : conventional material removal model

1. **Wafer surface [SiO_2 film] becomes softer in alkaline solution remarkably**

   → Soft hydration layer [$Si(OH)_4$] is formed on wafer surface

2. **Adhesion force applies to the stylus tip**

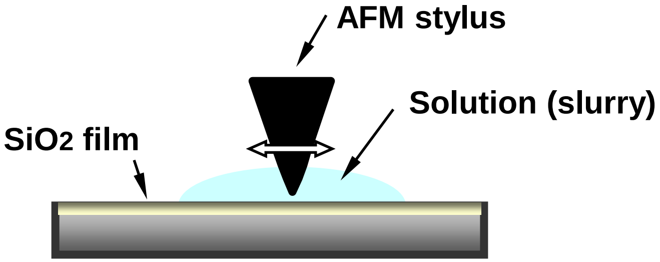
   → Fine particles in slurry are drawn to wafer surface

3. **The stylus tip is bonded with the wafer surface after contact on it**

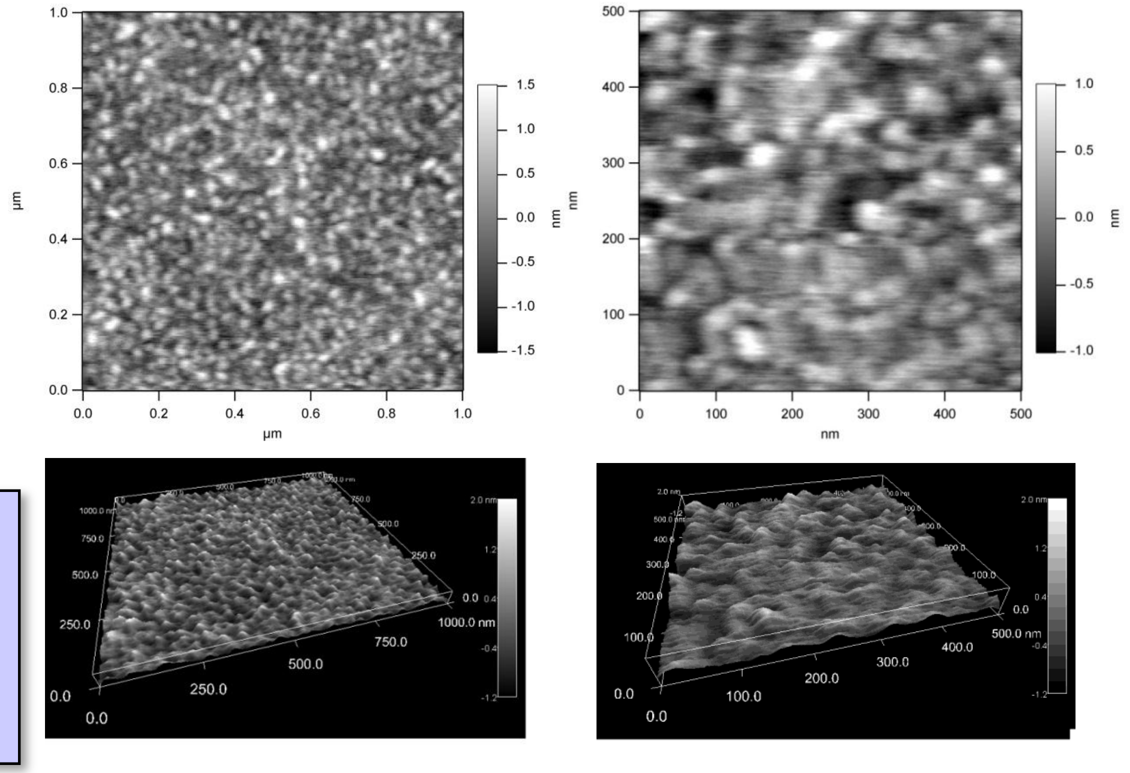
4. **Sticking material is observed at the tip of stylus after contact wafer surface, and sticking material is considered as "SiOx"**

As a third step, how the mass of particles behave in the space between polishing pad and wafer should be investigated.

Observation of the mass of particles on SiO_2 film surface



10 min after solution dropped, measured in solution as it is.



AFM : MFP-3D (Asylum Technology)
Stylus : Si
Wafer : SiO_2
Solution : SiO_2 particles + NH_4OH (LNA2000)
Concentration : 12.6 wt%
Particle diameter : approx. 23 nm(#2)

1. **Particles are accumulated on the surface of wafer, and arrayed packed, periodically and uniformly.**
2. **Distances between two particles are approx. 60 – 80 nm.**

Particles distribution in solution

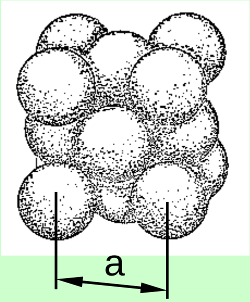
■ Specifications of slurry

SiO_2 particle :

primary diameter : 14.7 nm,

secondary diameter : 23.2 nm

concentration : 12.6 wt%



Lattice constant : a

Proximity distance : $\frac{\sqrt{2}}{2}a$

Face Centered Cubic structure

■ assumption

(1) SiO_2diameter : ϕ 23nm

(2) Distribution as face centered cubic

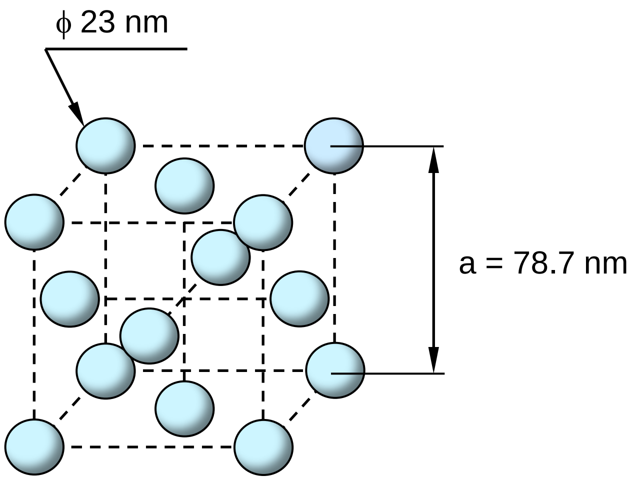
(3) Concentration : 12.6 wt%

(a) Number of particles in 1cc : 2.74×10^{18}

(b) distance between particles :

Lattice constant : 78.7nm

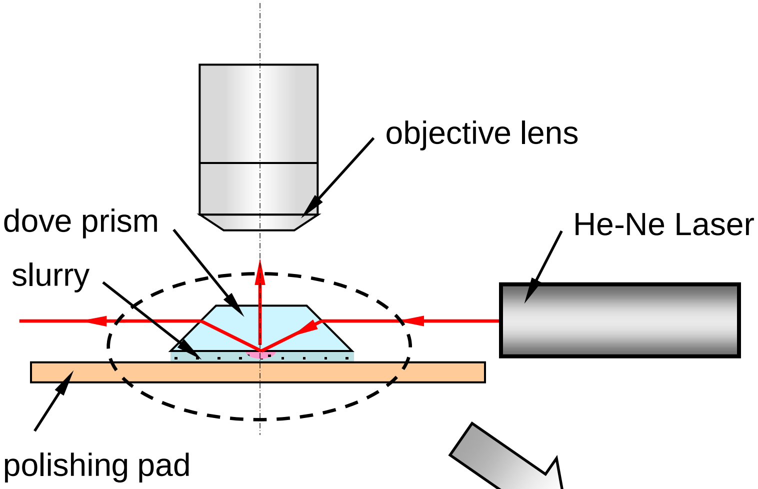
Proximity distance : 55.6nm



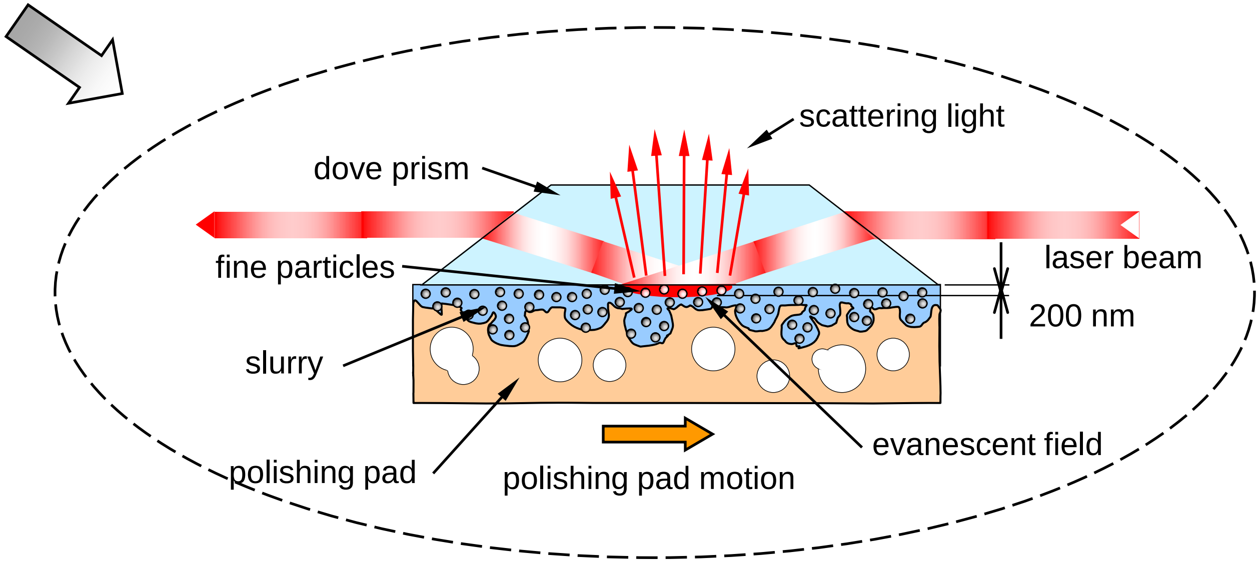
Fine particles would disperse in slurry as "FCC" structure

An attempt for observation fine particles in dynamic slurry flow

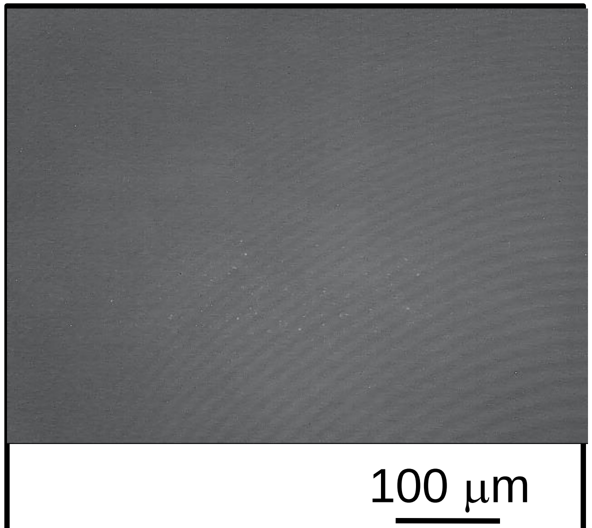
☑ Fine particles in slurry are observed with **evanescent light field** in dynamic motion



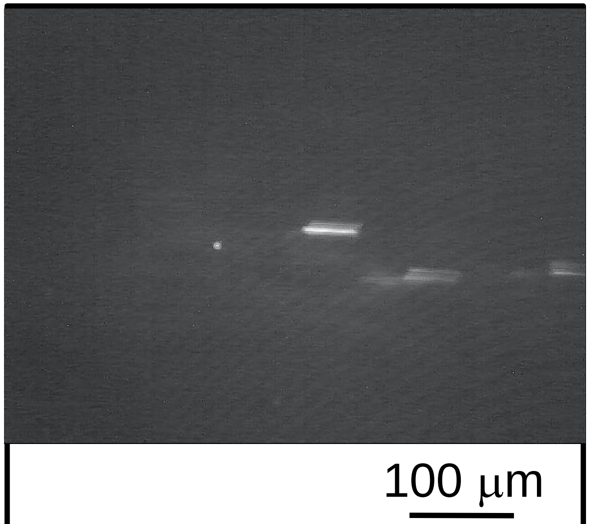
slurry	Colloidal Silica slurry	Ceria slurry
Particle dia. [nm]	300	500
Observation area	250x330 μm	
camera	DS-F11 (Nikon)	
Playback speed	X 21	



Observation movie



coloidal silica slurry



ceria slurry

Observation movies (60 fps)

Observation condition

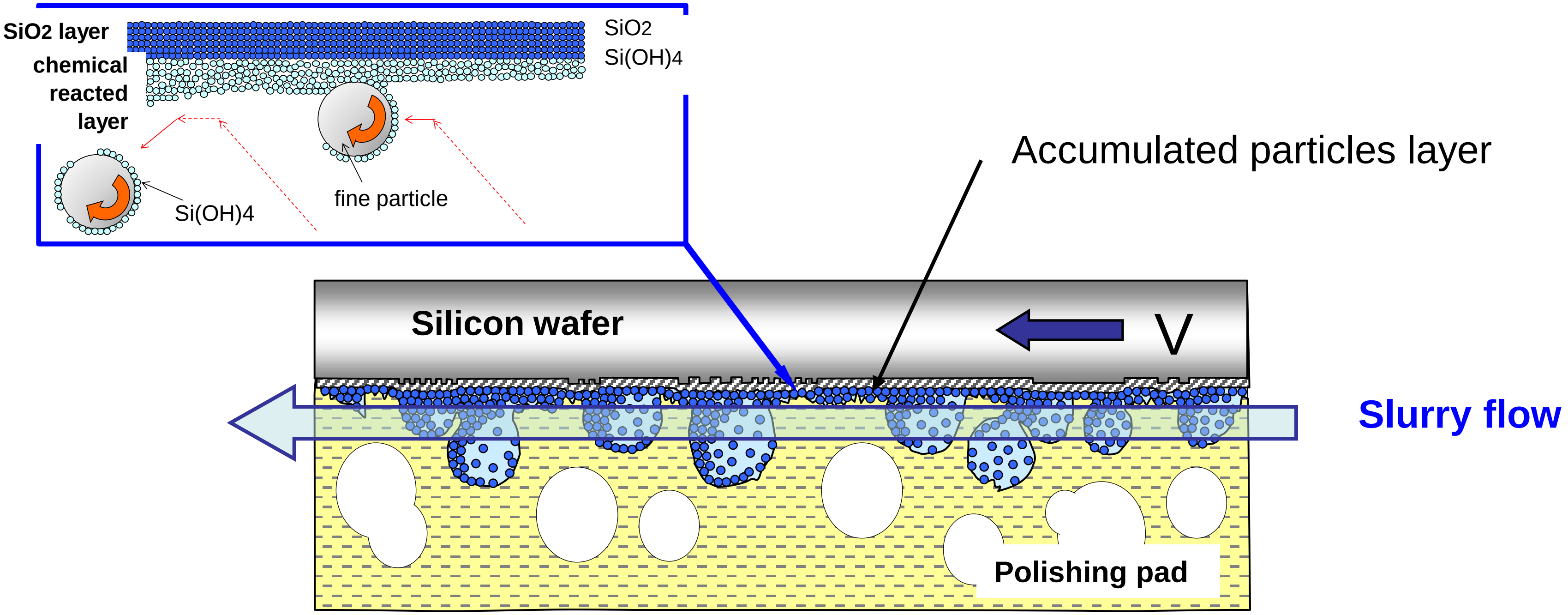
slurry	coloidal silica slurry	ceria slurry
particle diameter[nm]	300	500
pressure[kPa]	13.8	
rotation speed[/min]	1	
relative speed[mm/s]	2.9	
polishing pad	IC1000/Suba400 No-Groove	
high speed camera	VW6000 (KEYENCE)	
flame rate[fps]	60	
playback speed	4X	
observation area	375 μm × 500 μm	
laser type	He-Ne laser (wavelength:632.8nm)	

Particles move slowly in the slurry flow on near surface of glass.

These particles would work as removing materials with adhesion.

Predicting images of material remoival phenomena

May 11, 2011



1. Slurry flows into the thin space between wafer and polishing pad
2. Slurry particles are drawn and stick to the wafer surface
3. Slurry particles contact and roll on the wafer surface, and adhere the atoms from the wafer surface
4. With the motion of the mass of particles, material removal progress continuously

Conclusion

1. Material removal mechanism for SiO_2 CMP was investigated.

2. Contact area between polishing pad and wafer is extremely small, then it is hardly considered that micro cutting by fine particles is carried out.

3. Mechanical property of wafer surface and fine particle’s function in slurry were investigated with AFM.

4. Hydration layer is formed on the wafer surface, and bonding strength become lower. Fine particles in slurry flows and contact at the wafer surface, and remove materials from the surface with adhesion.

5. In slurry, a great mass of particles dispersed regularly, and these particles remove material continuously.

March 11, 2011　Big Earthquake & Tsunami attacked in Eastern Japan

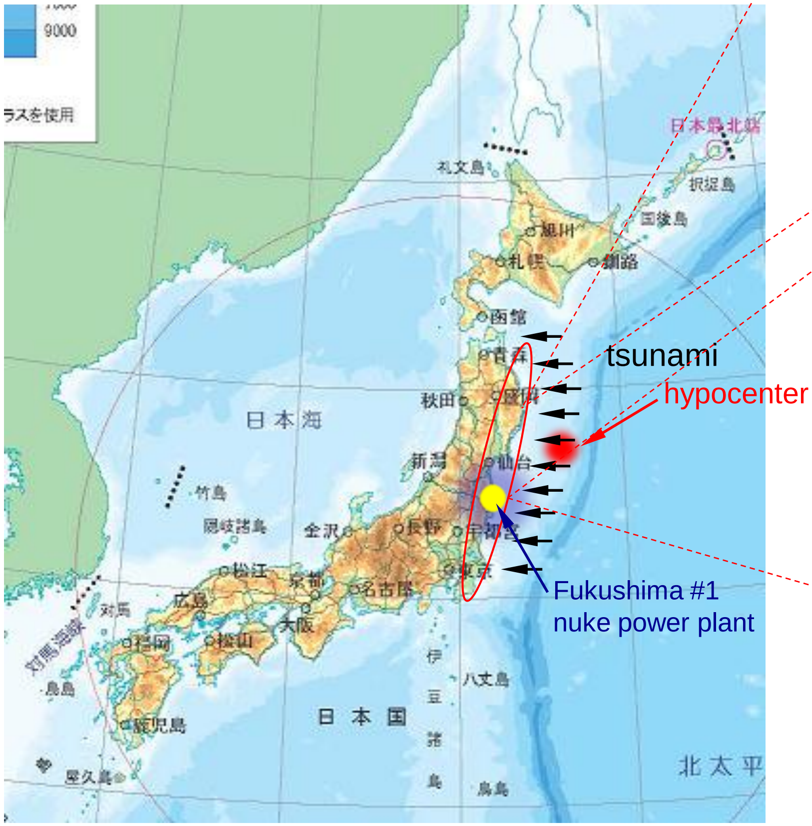
May 11, 2011

Location of disaster area

May 11, 2011

Three damages hit Japan

1. Earthquake
2. Tsunami
3. Nuclear power plant accidents



Fukushima #1 nuclear power plant

The dead : *14,949*
The missing : *9,880*
as of May 10, 2011

Thank you for your warmhearted support to JAPAN !

May 11, 2011

ありがとうございました

Thank you for your attention !

Keiichi Kimura

Kyushu Institute of Technology

JAPAN

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Academic Programs ~Bachelor~

Tobata Campus

School of Engineering

Since 1909

- Mechanical and Control Engineering
- Civil and Architectural Engineering
- Electrical Engineering and Electronics
- Applied Chemistry
- Materials Science and Engineering
- Integrated System Engineering

Iizuka Campus

School of Computer Science and Systems Engineering

Since 1986

- Artificial Intelligence
- Computer Science and Electronics
- Systems Design and Informatics
- Mechanical Information Science and Technology
- Bioscience and Bioinformatics

Academic Programs ~M.S. and Ph.D~

Tobata Campus

Graduate School of Engineering

- Mechanical and Control Engineering
- Civil and Architectural Engineering
- Electrical Engineering and Electronics
- Materials Science
- Applied Science for Integrated System Engineering

Iizuka Campus

Graduate School of Computer Science and Systems Engineering

- Information Science
- Information Systems
- Creative Informatics

Wakamatsu Campus

Graduate School of Life Science and Systems Engineering

Since 2000

- Biological Functions and Engineering
- Brain Science and Engineering

Number of Students

The total number of students is 6,063
(4,363 undergraduate and 1,700graduates).

Campus	Schools (Bachelor and M.S./Ph.D)	Number of Students
Tobata	School of Engineering	2,446
	Graduate School of Engineering	779
Iizuka	School of Computer Science and Systems Engineering	1,917
	Graduate School of Computer Science and Systems Engineering	539
Wakamatsu	Graduate School of Lice Science and Systems Engineering	382
	Total	6,063

Kyutech
Kyushu Institute of Technology

Number of Academic Staff

The total number of Academic Staff is 370.

Campus	Classification	Professors	Associate Professors	Lecturers	Assistant Professors	Number of Faculties
Tobata	Faculty of Engineering	63	63	1	37	164
Iizuka	Faculty of Computer Science and Systems Engineering	46	50	2	28	126
Wakamatsu	Graduate School of Lice Science and Systems Engineering	22	13	1	9	45
	Other*	14	12	1	8	35

Total **370**

*Other:
- -Center for Student Health
- -Information Science Center
- -Center for Microelectronic Systems
- -Collaboration Center
- -Center for Instrumental Analysis
- -Network Design Research Center
- -Advanced Mold and Die Technology Center
- -Eco-Town Collaborative R&D Center for the Environment and Recycling
- -Science Education Center

Kyutech
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