Comprehensive Investigation of Sequential Plasma Activated Si/Si Bonded Interface for Nano-integration

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Outline

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  - Surface prerequisites
  - Issues in current wafer bonding techniques
- Sequential Plasma Activated Bonding (SPAB)
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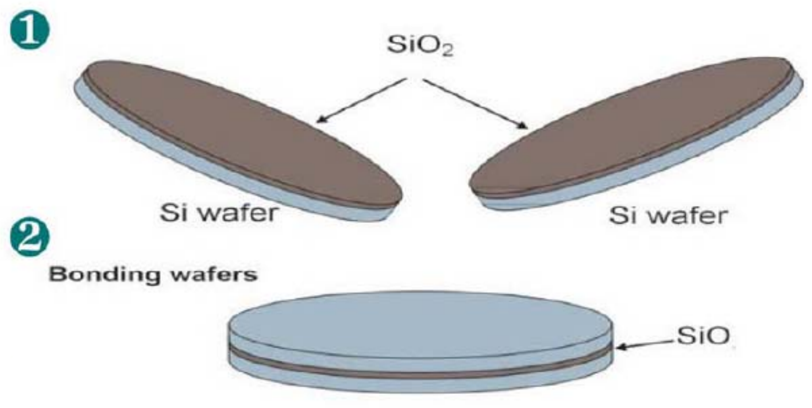
  - SPAB Mechanism
- Surface and bonded interface characterization
- Perspective of this study
- Conclusion

What is wafer bonding?

Wafer bonding refers to the adhesion of two mirror polished, smooth and clean surfaces without any adhesives, external forces and wet chemical processing. At room temperature the bonding is due to inter-atomic attractive forces.



Wafer bonding process

Ref. Christiansen *et al* Procee. IEEE, 94 (2006).

Applications of wafer bonding

- ✓ Fabrication of Silicon-On-Insulator (SOI) substrate, (Smart-cut, ELTRAN)
- ✓ 3D integration of micro/nano-electromechanical-systems (M/NEMS)
- ✓ Bonding similar and dissimilar materials (with different thermal and lattice parameters) for photonics and optoelectronic applications, VCSEL
- ✓ Fabrication of patterns for self-assembly of molecules, nanowires or quantum dots using twist bonding.

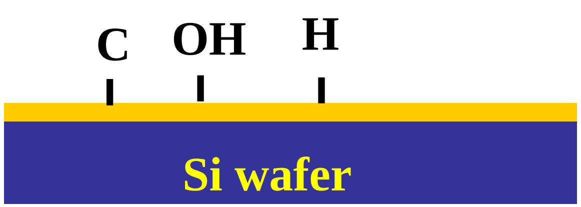
Wafer surface pre-requisites

- Flatness and smoothness (rms surface roughness < 0.5 nm)
- Cleanliness (remove particulates and contaminants)
- Surface activation (chemical or plasma treatment to increase wafer surface energy)

Plasma treatment or activation has twofold benefits:

✓ the number of bonding sites (OH^-) greatly increases

✓ It generates nanoscopic surface porosity in the silicon dioxide, which allows for absorbing reaction products from the bonding reaction (typically water molecules) more easily



Before activation

After activation

Reaction byproduct

$$\equiv SiOH + HOSi \equiv \longrightarrow \equiv Si\text{-}O\text{-}Si \equiv + H_2O$$

Issues in current wafer bonding techniques

- Wet chemical processing
- High external force
- Post-bonding annealing
- Dissimilar material bonding is not possible

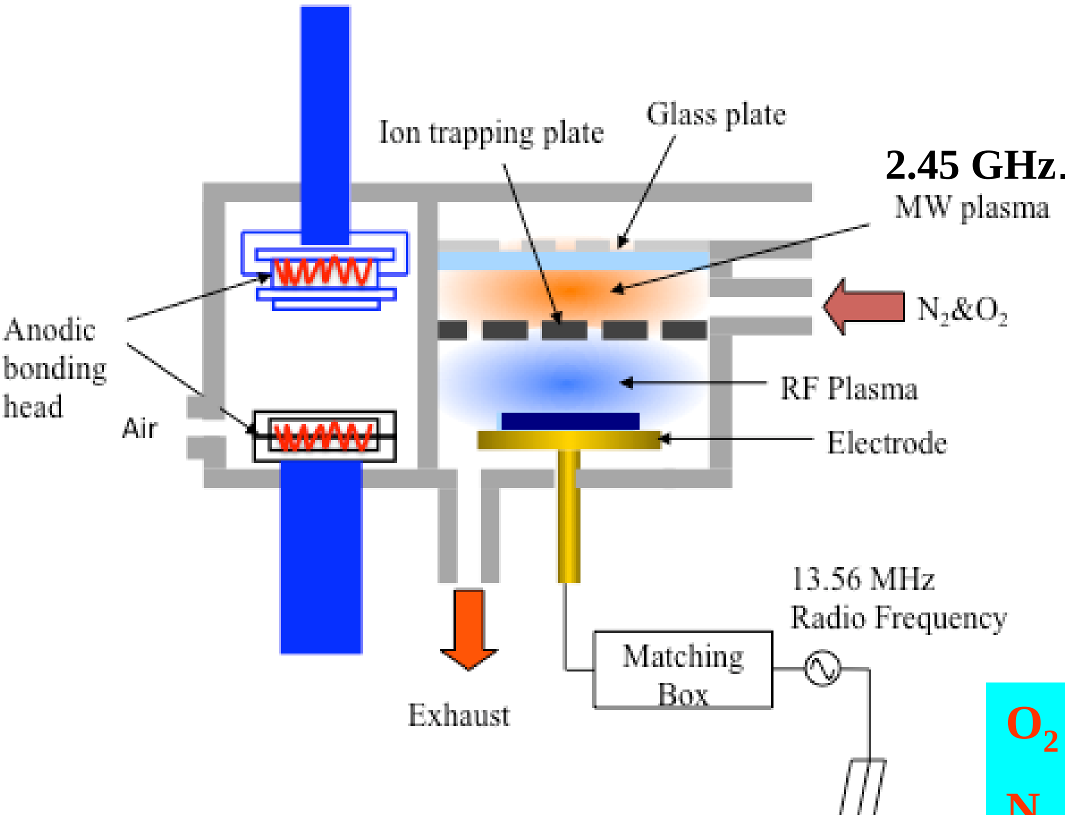
Therefore, current wafer bonding techniques are not suitable for bonding/integration of nanostructures, such as nanowires, carbon nanotubes or quantum dots due to their delicate nature.

Potentials of sequential plasma activated bonding

- No wet chemical processing
- No external force
- No post-bonding annealing
- No adhesives
- Spontaneous bonding
- At room temperature, the bonding strength achieved is equivalent to that of bulk material
- Dissimilar material bonding is possible

Hence, SPAB is applicable to integrate nanostructures such as NWs, CNTs or QDs

Sequential Plasma Activated Bonding (SPAB) Process



Hybrid plasma bonding system

O_2 RIE plasma followed by N_2 MW plasma is used for surface activation.

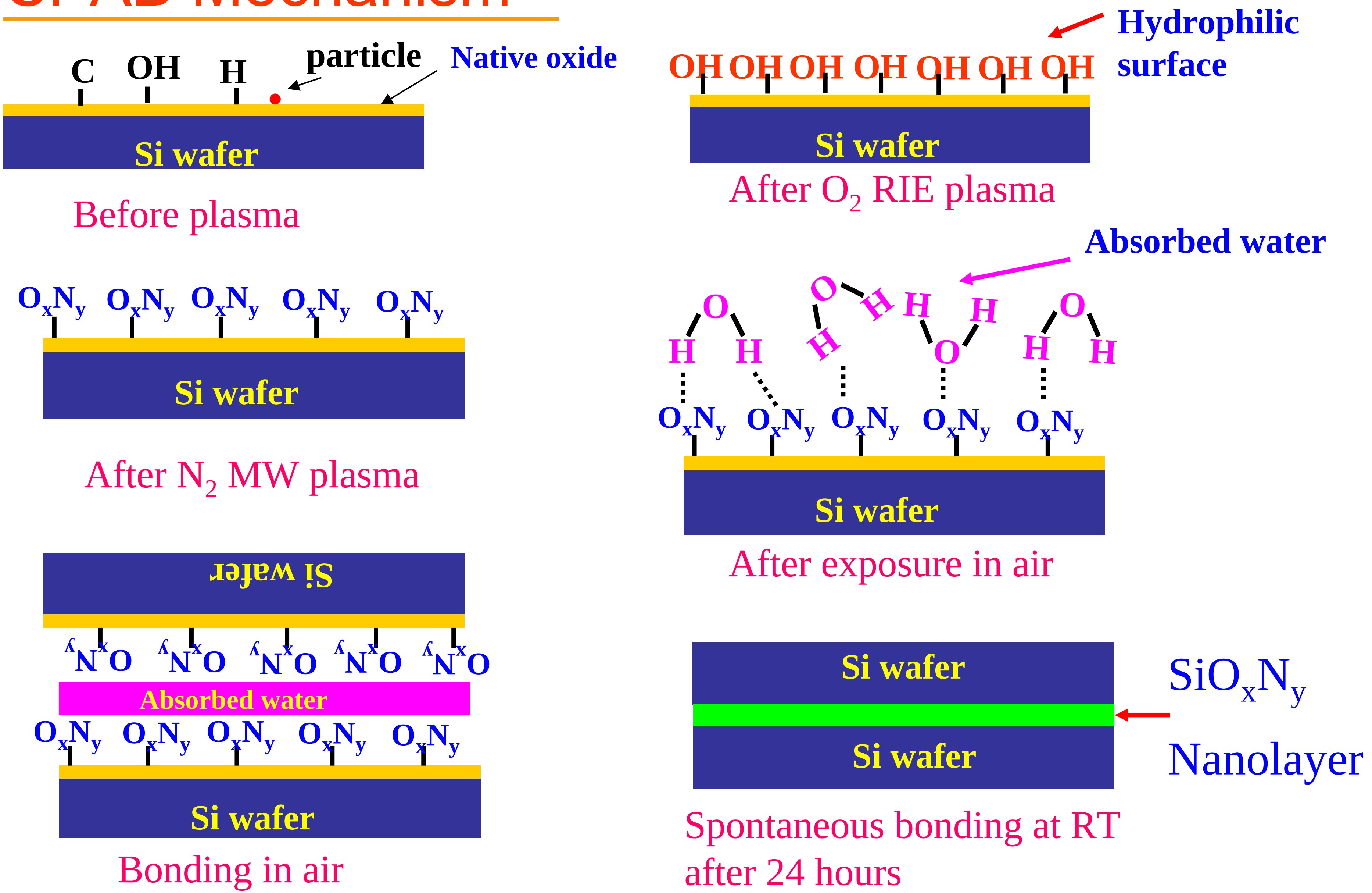
After sequential plasma activation, two wafers are bonded in clean room ambient by hand applied pressure

O_2 RF-RIE: 50- 300 W, 40-120 Pa, 5-300 s

N_2 MW: 2000 W, 100 Pa, 30 s

O_2 RIE plasma removes contaminations from the surface.
N_2 MW radical creates chemically reactive wafer surfaces with high surface energy.

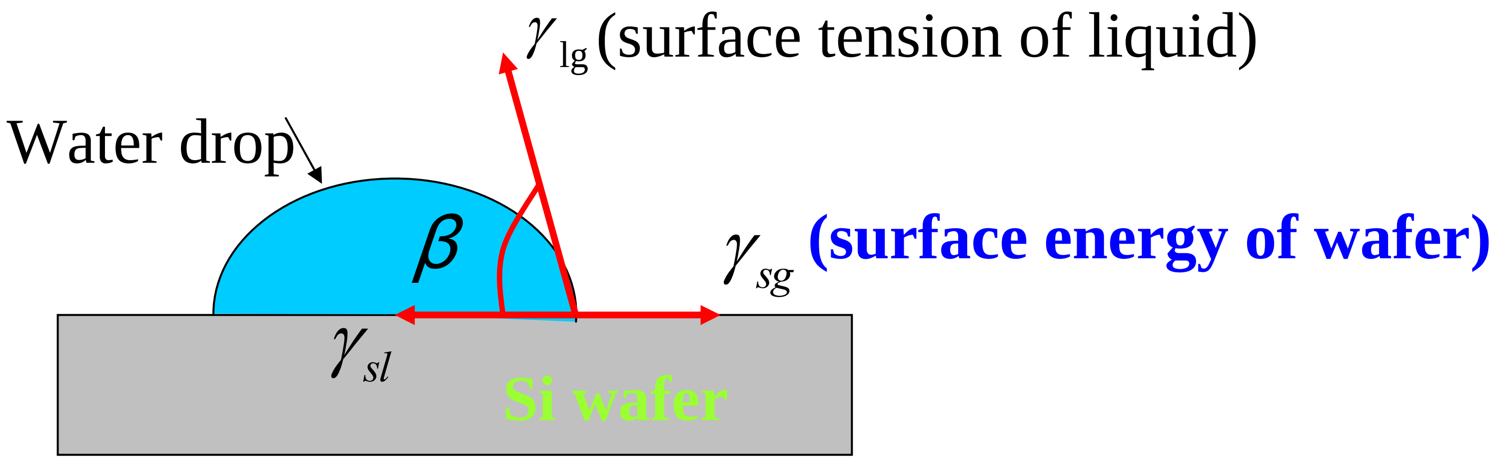
SPAB Mechanism



Ref. T. Suga et al, 2004.

Wafer surface characterization -
Contact angle measurements

Surface hydrophilicity can be measured by Contact angle of water on wafer surface, which also represents wafer surface energy

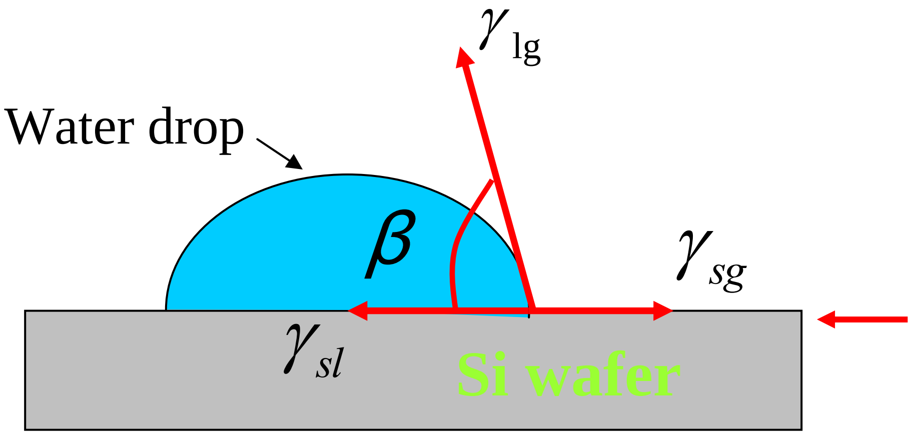


surface energy **Contact angle**

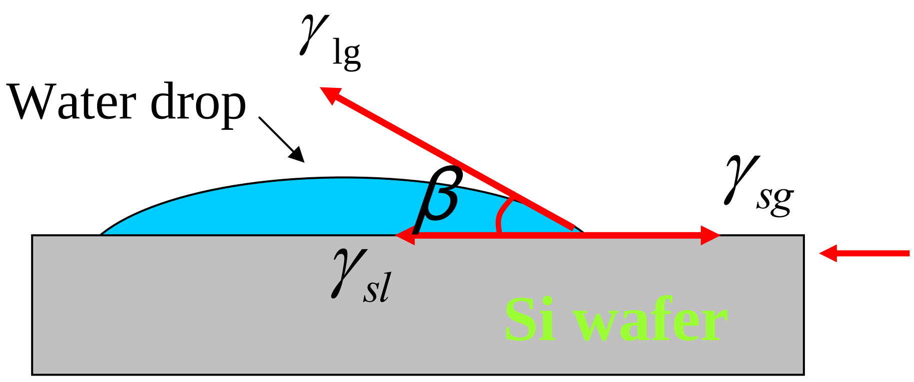
Young equation, $\uparrow \gamma_{sg} = \gamma_{sl} + \gamma_{lg} \cos\beta \downarrow$

The lower the contact angle, the higher the surface energy of the wafer.

Wafer surface characterization-*continued*



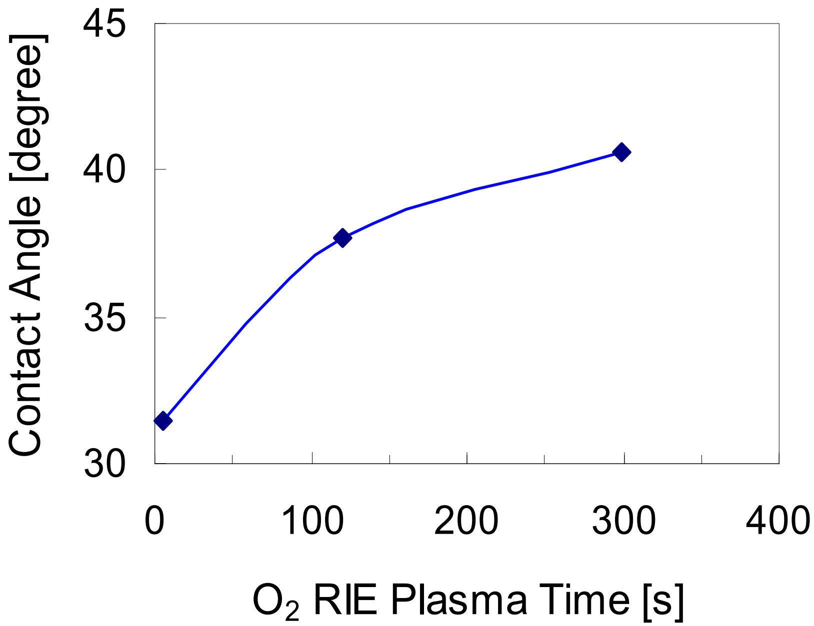
Hydrophobic surface, $\beta > 45°$

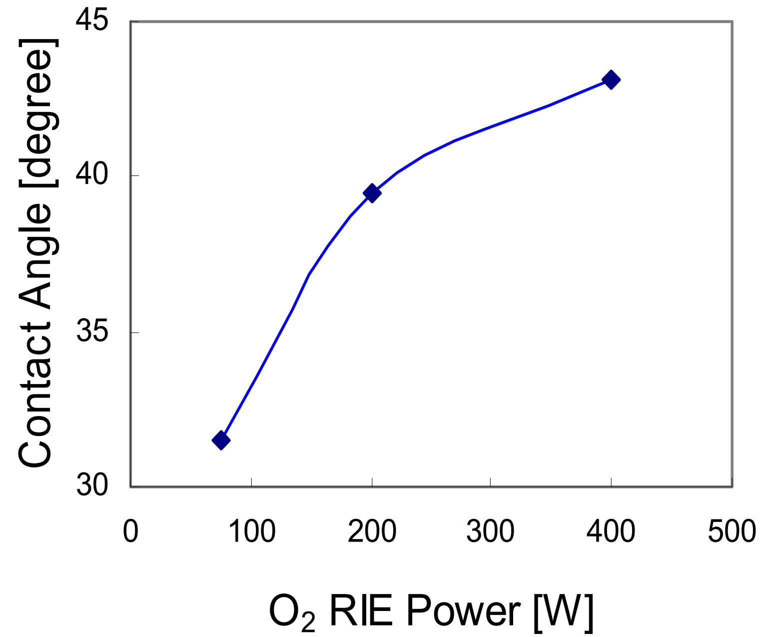


Hydrophilic surface, $\beta < 45°$

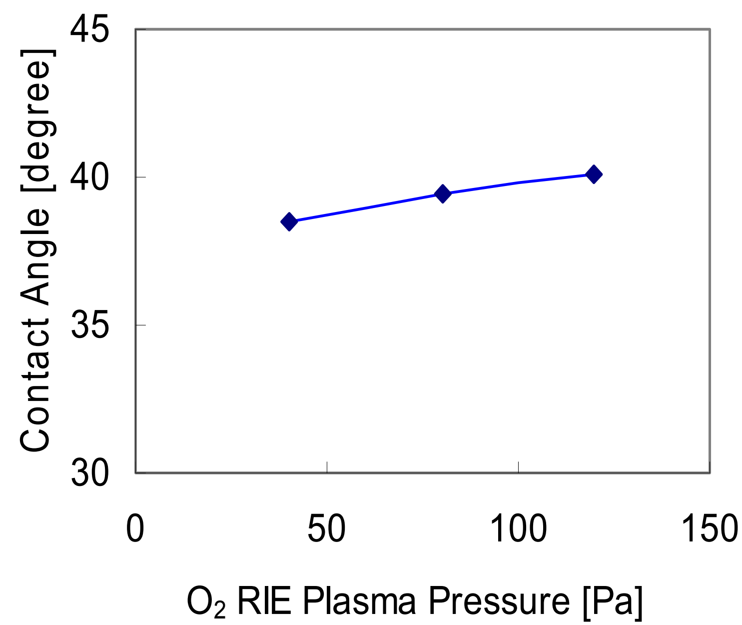
Hydrophilic surfaces are easier to bond than hydrophobic surfaces

Wafer surface characterization-
Influence of plasma parameters



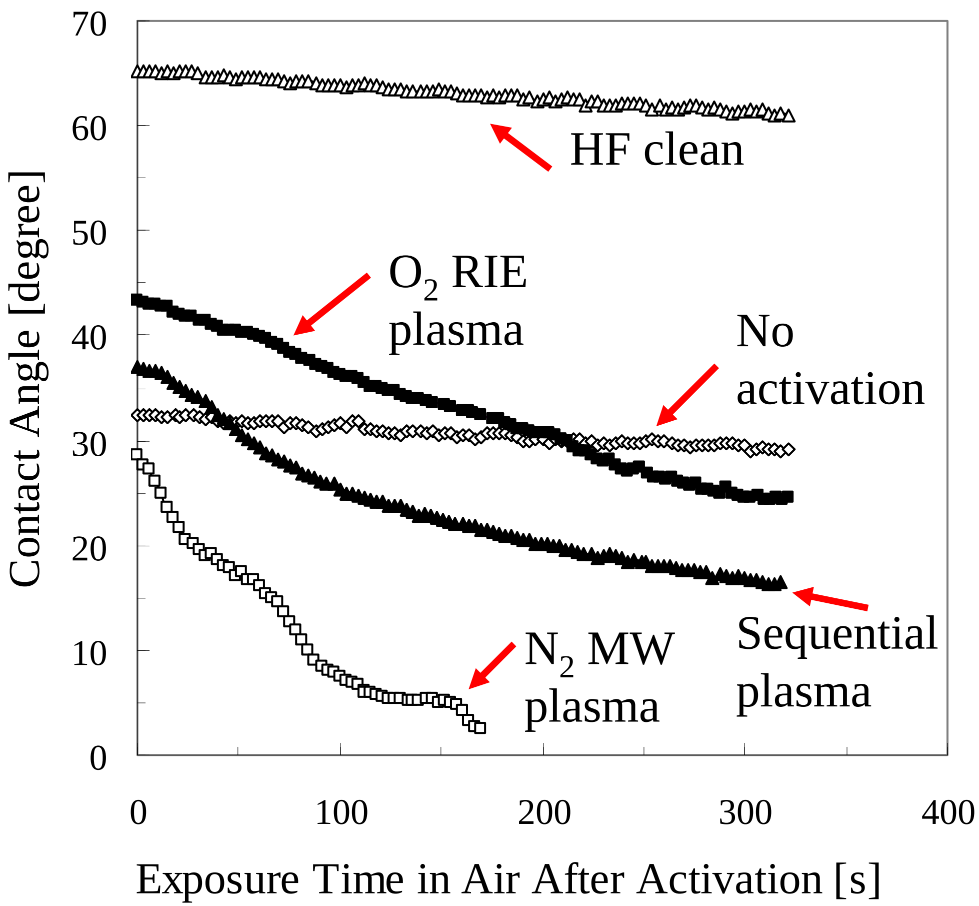


Contact angle increases and hence surface energy decreases with O_2 RIE plasma activation time, power and pressure.



Plasma time and power have higher influence than plasma pressure

Surface characterization –*Investigation of surface reactivity*

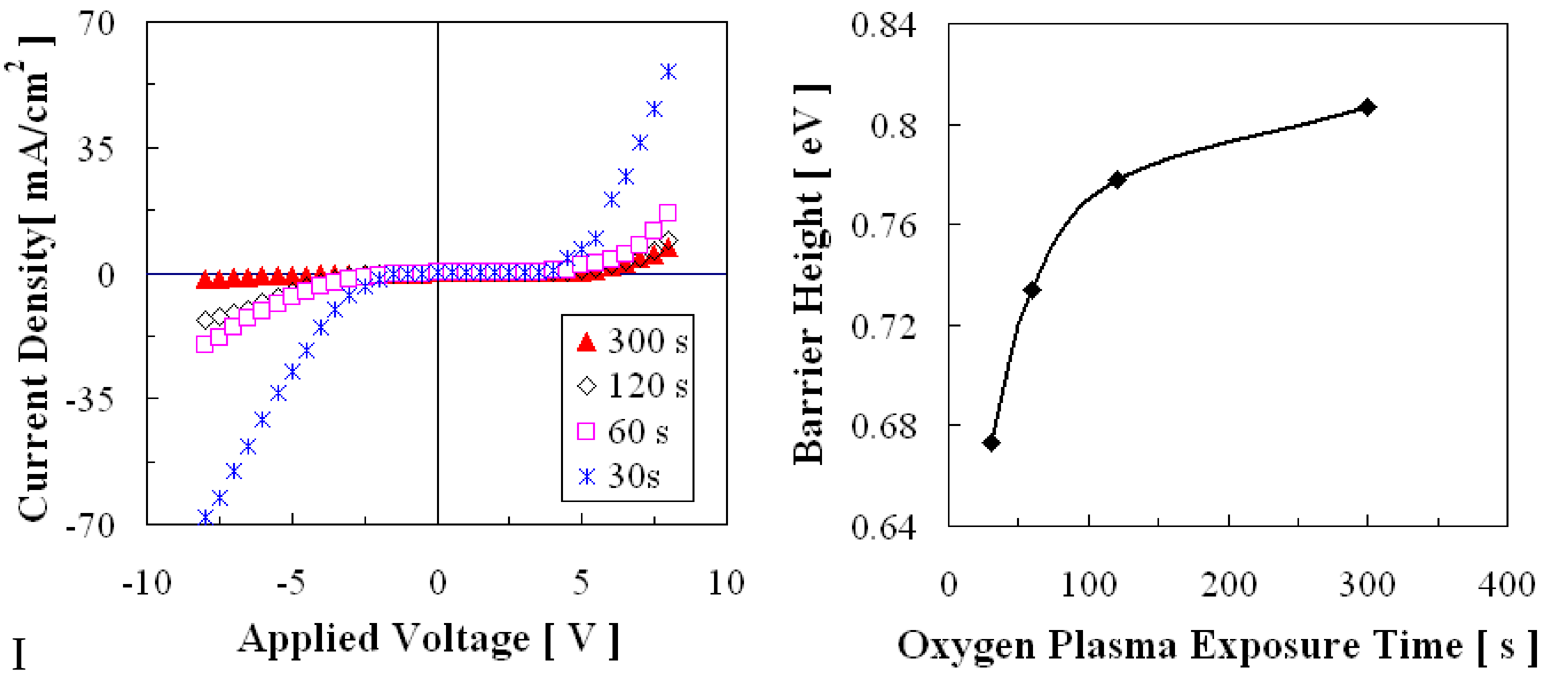


The rate of change of contact angle with time refers to surface reactivity

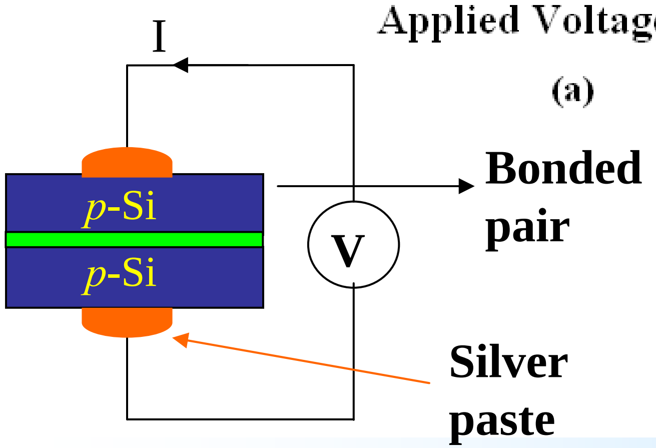
Plasma activated surfaces are highly reactive and has higher surface energy compared to nonactivated surfaces.

N_2 MW plasma treated surface is highly reactive compared to O_2 RIE treated surface

Electrical characterization of interfaces-
Influence of plasma activation time



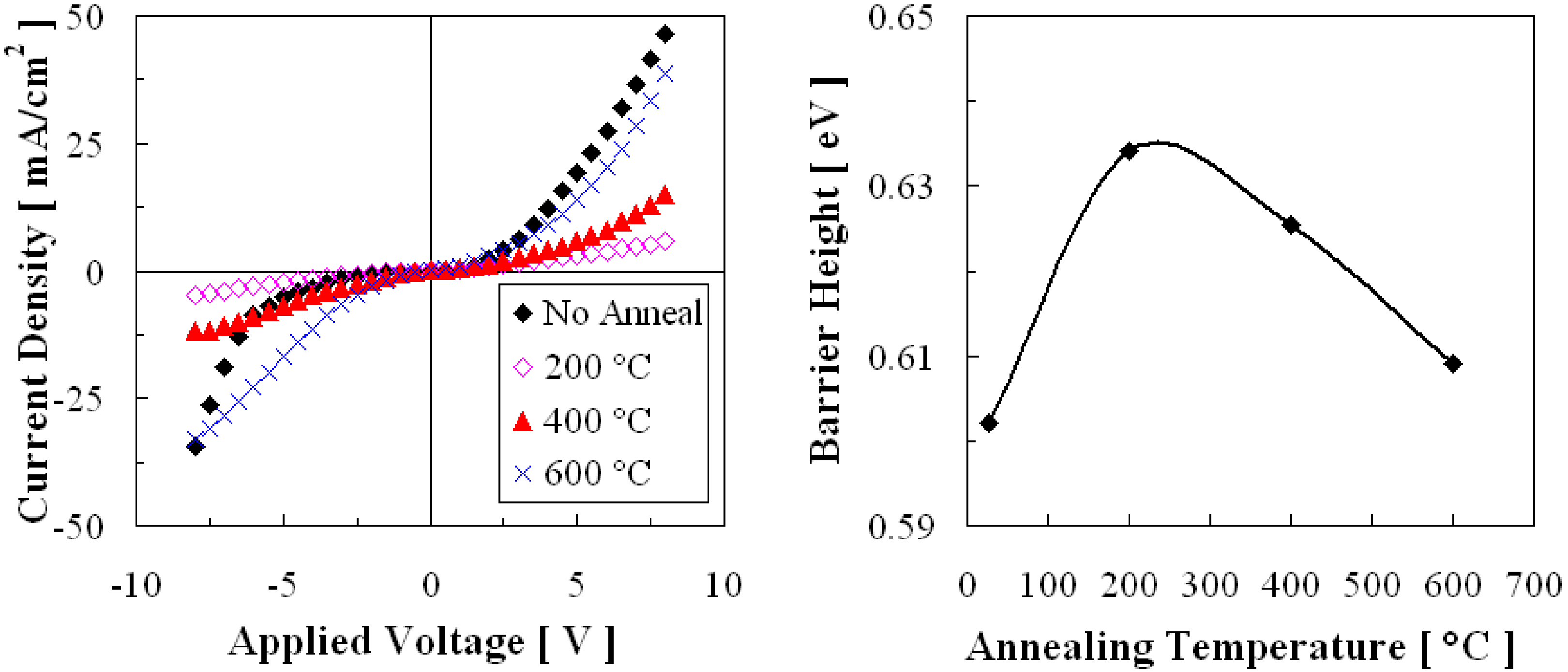
(a) (b)



Barrier height increases with plasma activation time

Oxide layer grows with O_2 RIE plasma time. O_2 Plasma increases defects, fixed charges and traps that reduces current and increases barrier height.

Electrical characterization of interfaces-
Influence of post-bonding annealing



(a) (b)

To avoid lateral difference in density of interface states, a single bonded pair was annealed at different temperatures

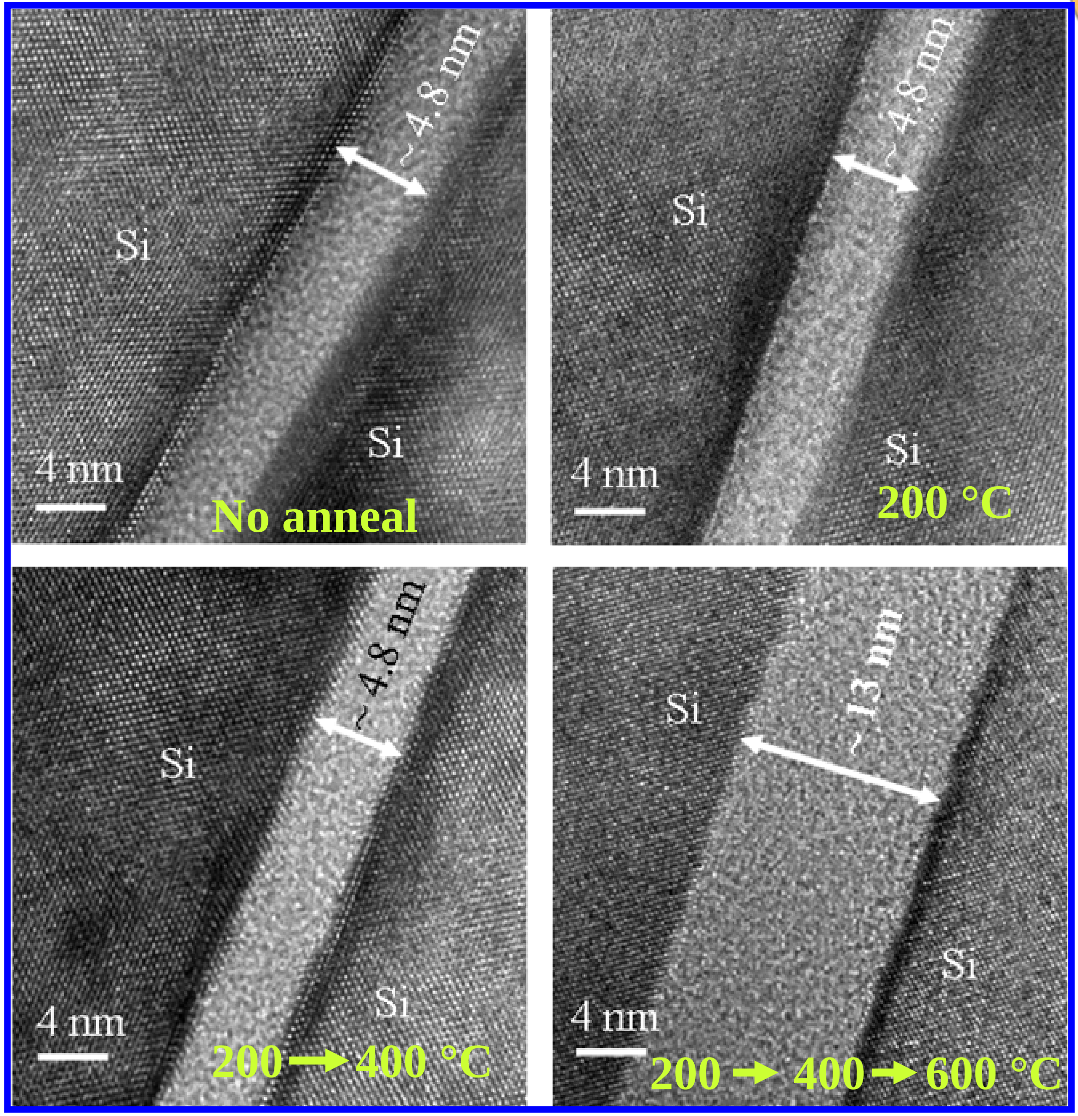
Barrier height increases after 200 and decreases after 400 and 600 °C

Nano-interface observation by HRTEM

Annealing	Interlayer thickness
No anneal	4.8 nm
200 °C	4.8 nm
400 °C	4.8 nm
600 °C	13 nm

At 600 °C, void density across the interface also abruptly increases, as observed by our IR images. Silicon oxidation and viscous flow of H_2 lead to abrupt change in oxide thickness and void density.

$$Si + 2H_2O \longrightarrow SiO_2 + 2H_2$$



HRTEM images of Si/Si bonded interfaces

Perspective of this study

Different techniques have been proposed to integrate nanostructures/NWs

Such as:

- **Diffusion bonding**
- **Ultrasonic nanowelding**
- **Adhesives and solder bonding**
- **Thermocompression bonding**

Issues in these bonding techniques for nanostructures/NWs integration are:

- **Adhesive and solder bonding results in reduced current transport**
- **Diffusion and thermo-compression bonding requires high temperature and pressure**
- **Ultrasonic vibrational force may break NWs due to their delicate nature**
- **Reduced mechanical stability of the bond**
- **Chemical sensitivity of nanostructures.**

Prospective of this study

SPAB offers-

- spontaneous bonding
- diverse materials
- without adhesive
- without high temperature
- no pressure and chemicals

it may open up opportunities for the integration of nanostructures at room temperature.

Conclusions

❖ Sequential plasma activation offers high reactive surface required for spontaneous bonding at room temperature.

❖ Surface energy and current transport across the bonded interface can be controlled using the activation parameters.

❖Post-bonding annealing degraded the current transport across the interface.

❖Nanoscale bonding was confirmed by HRTEM. Annealing only at 600 C increased the thickness of amorphous oxide due to silicon oxidation and viscous flow of hydrogen gas.

❖ This comprehensive investigation can facilitate spontaneous nano-integration of dissimilar materials without chemicals, external force, adhesive and heating.

Acknowledgments

1. **Natural Science and Engineering Research Council (NSERC)** of Canada, and an infrastructure grant from the **Canada Foundation for Innovation (CFI).**

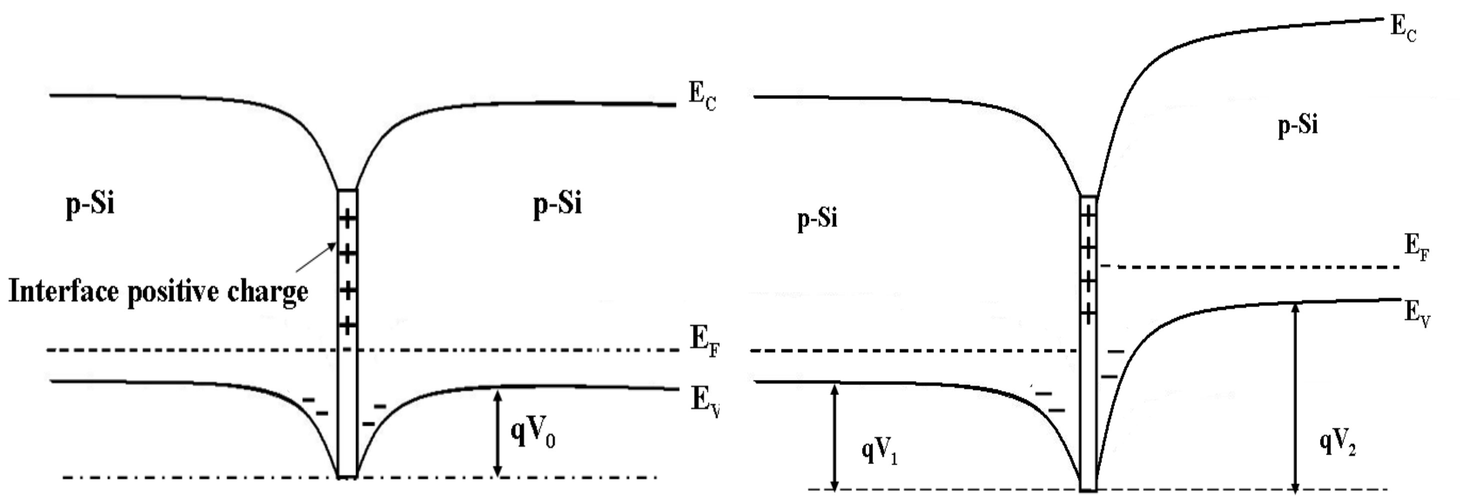
2. **Prof. J. Deen, McMaster U.** for his support and assistance in establishing nano-bonding and interconnection system **(NBIS)** at McMaster University.

3. **Prof. Tadatomo Suga, U. Tokyo** for the development of the sequential plasma activated bonding method.

4. **A. Yamauchi of Bondtech Corporation and G. Kagami of Shinko Seiki Co. Ltd. Japan** for their assistance in the construction of the hybrid plasma bonding system.

Thanks for your attention

Energy band diagram of the *p*-Si/*p*-Si bonded interface



Schematic Energy band diagram of a *p*-Si/*p*-Si bonded structure at (a) zero bias, (b) with applied bias

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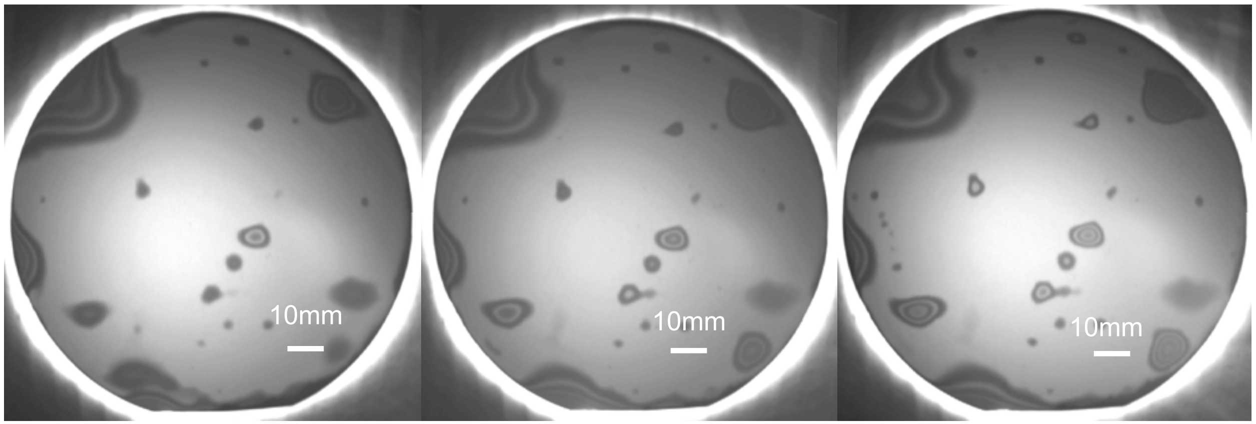
Reasons for using silver paste for electrodes:

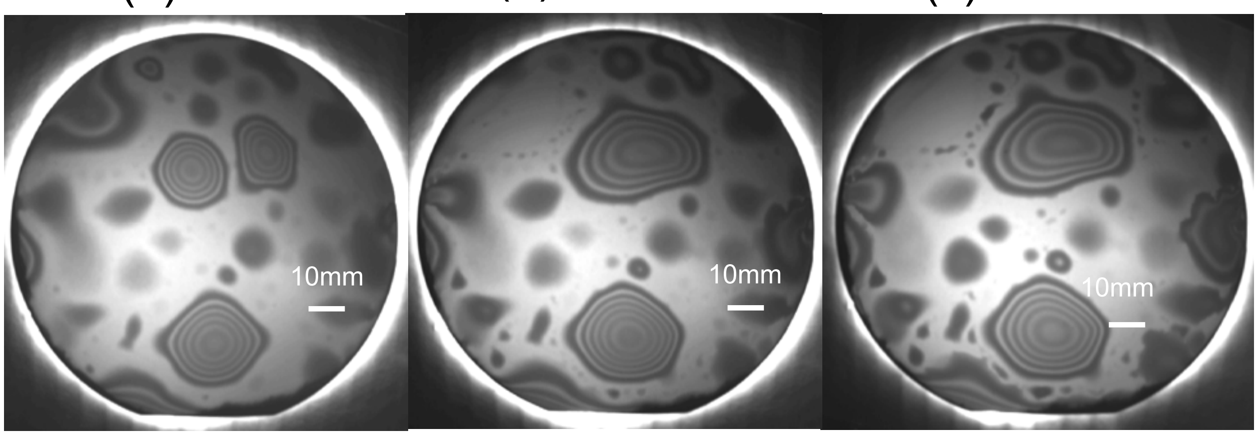
- To avoid external temperature effects (temperatures during electrode deposition) on the bonded interface properties
- To avoid possible sintering of the electrode metal and silicon at high annealing temperatures

EELS electron energy loss spectroscopy

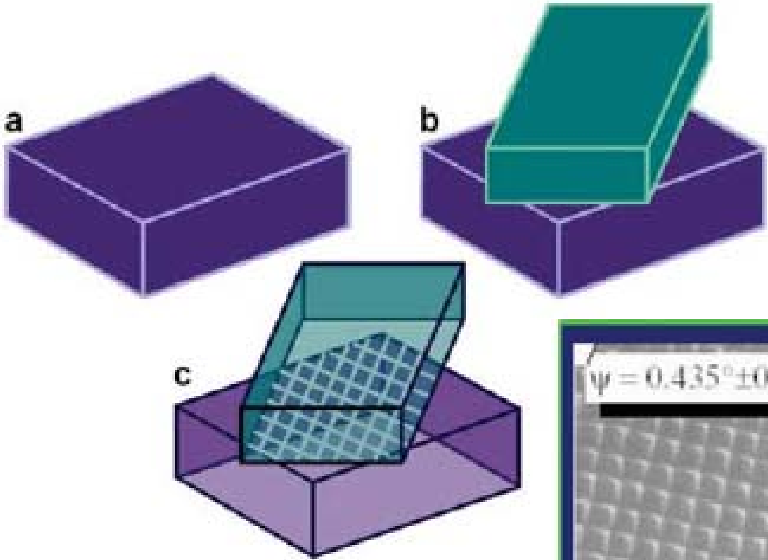
Infrared (IR) Transmission Images of bonded pair after different annealing steps



(a) RT (b) 200^{o}C (c) 400^{o}C



(d) 600^{o}C (e) 800^{o}C (f) 900^{o}C



Twist bonding for nanowires growth

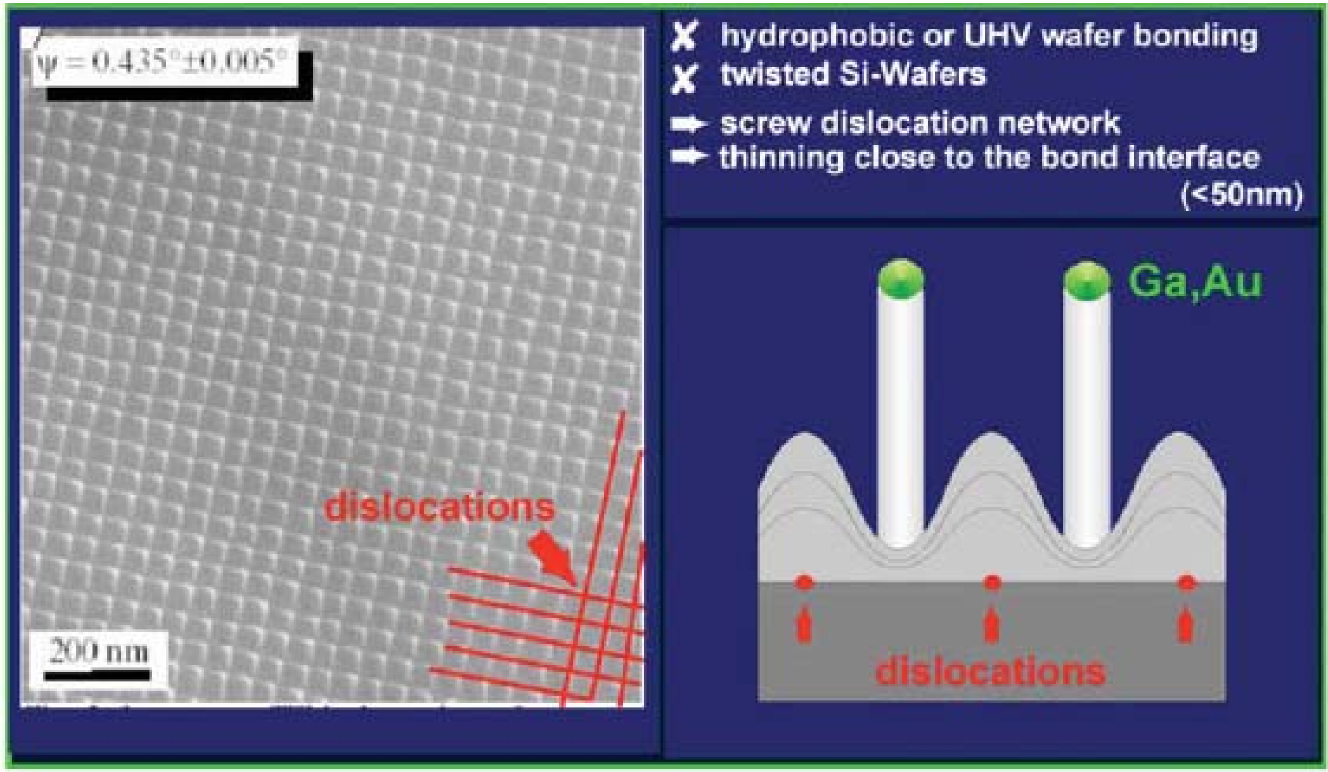
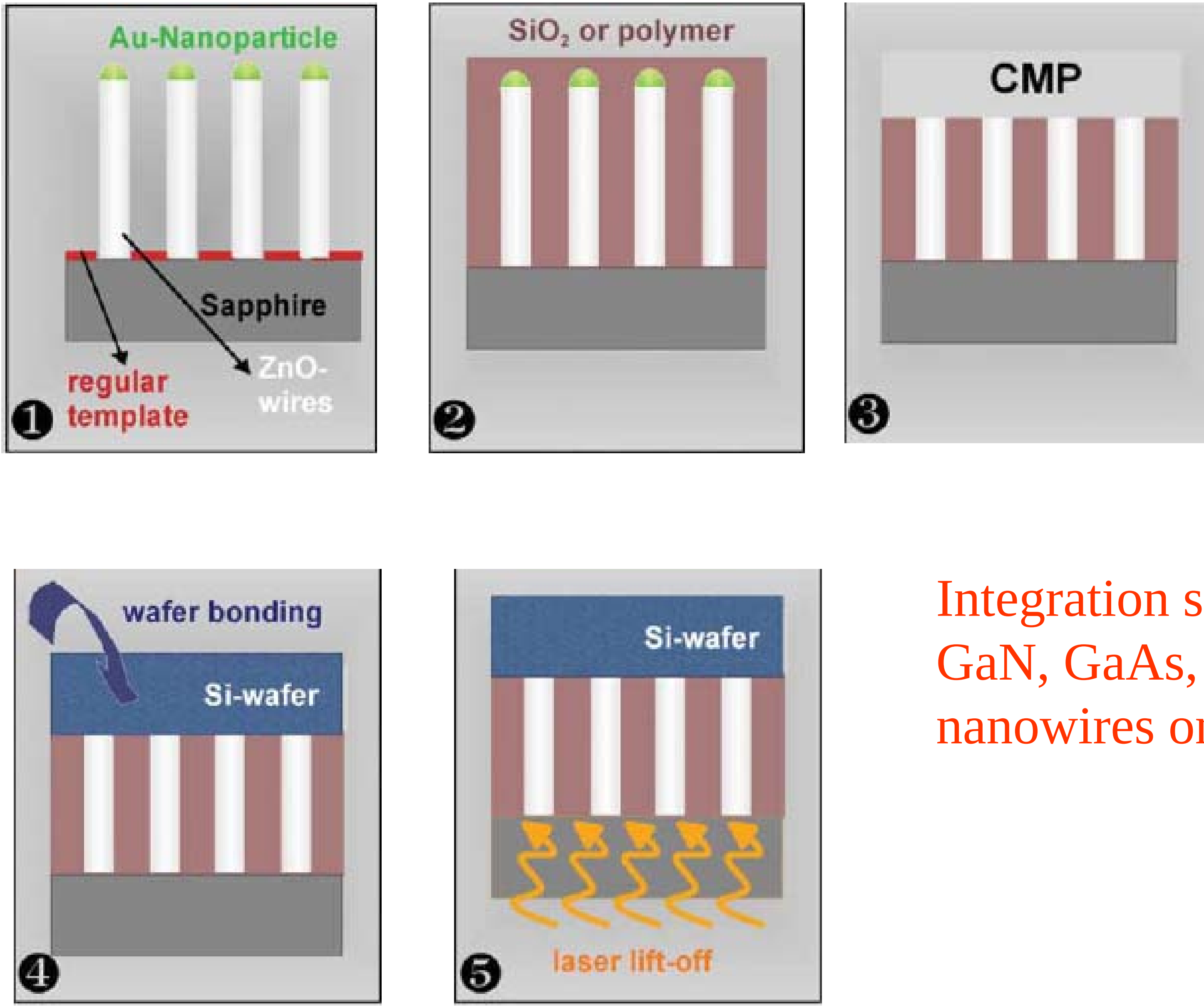


Fig. 43. *TEM plane view micrograph of an ordered array of dislocations in a twist-bonded substrate (left, from [282]) and a possible way to use these substrates as wafer level templates for aligned growth of Si nanowires (right). Strain field of dislocations can be used to create periodic nanoscale ripples on the wafer surface (by etching or heteroepitaxial deposition [281]). Metal nanoparticles can be applied in the troughs of the template which can in turn serve as catalysts for nanowire growth.*

Christiansen *et al.*, IEEE, 94 (2006).



Integration scheme of GaN, GaAs, ZnO nanowires on Si wafers.

Christiansen *et al*., IEEE, 94 (2006).