Wafer-wafer bonding using silicides for high-temperature applications

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Stanford University

Primer on wafer bonding

- Thermocompression: Heat sticky material between two substrates
- Anodic: Diffusion of alkali ions between Pyrex glass and Si wafer
    - Performed at 180ºC to 500ºC
- Eutectic: bond with mixture that melts at lower temperature than constituents
    - Performed at 150ºC to 500ºC
- Fusion: stick together without intermediate
    - Ultra-clean, ultra-flat, chemically reactive surface (dangling bonds).
    - Ultrahigh temperature ~1000ºC

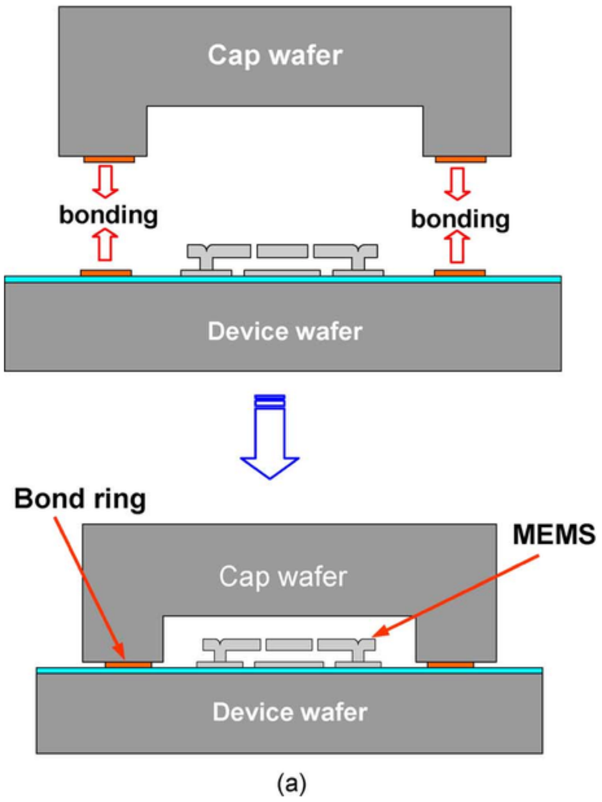
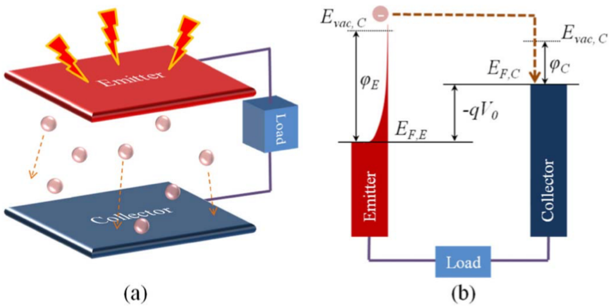


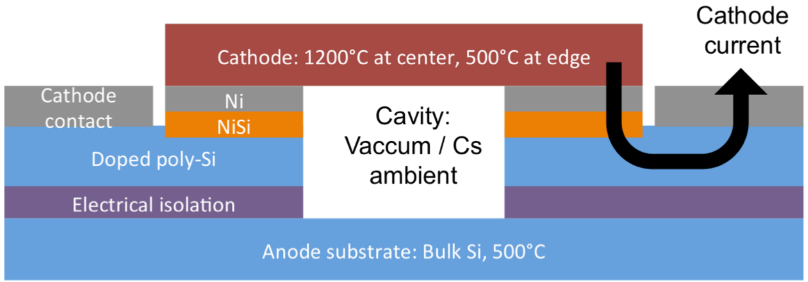
Figure adapted from He, R., Kim, C.J., *J. Micromech. Sys.*, 2007

Applications of nickel silicide wafer bonding

Packaging and integration for extreme environment MEMS devices

- Example application: vacuum package and vertical interconnect for MEMS thermionic energy converters
- NiSi forms at low (~250-450ºC) temperature, melts at higher (~900ºC) temperature
- Conductive: NiSi = 14-20 μΩ cm [1], $NiSi_2$ = 40-50 μΩ cm [1]
- May be compatible with corrosive environment, i.e. Cs vapor

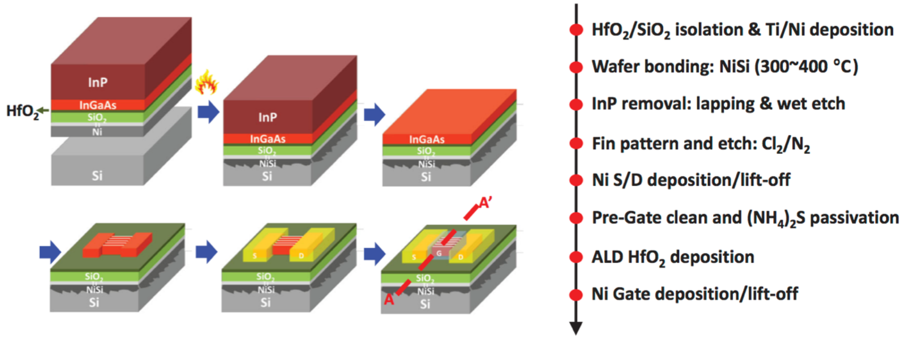


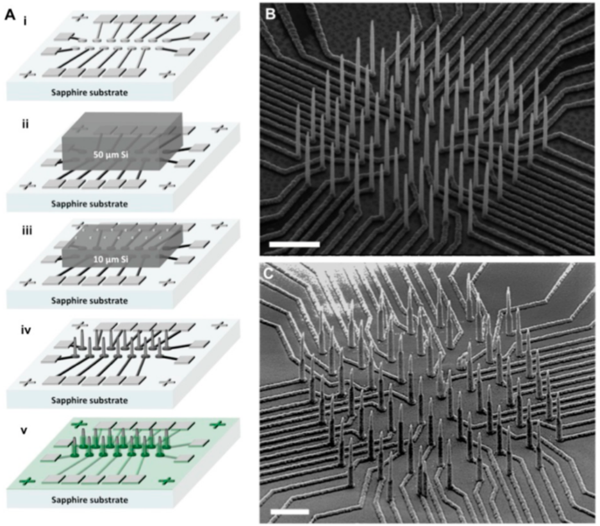


[1] Saraswat, K. "Interconnections: Silicides." EE311 Lecture slides. Stanford University.
Left figure from Lee, J.-H. *et al.*, *J. Micromech. Sys.* 2014

Applications of nickel silicide wafer bonding

More applications: hybrid/heterogeneous integration





Left: Integration of III-V onto Si by nickel silicide bonding, from Dai, X., *et al*. *Adv. Func. Mat.* 24, 4420-4426. (2014)

Right: Fabrication of Si nanowire arrays for neural recording by nickel silicide bonding and Si etch, from Liu, R. *et al. Nano Lett.* 17, 2757-2764. (2017).

Introduction to the SNF evbond

- EV501 bonder
  - Heating chuck with pressure plate in a vacuum chamber (7.5 x 10^{-6} torr)
  - Capable of doing anodic, eutectic, solder bonding
- Process parameters for tool
  - Bonding temperature, between RT-500ºC
  - Force applied by chuck, 0-3340N
  - Bonding time

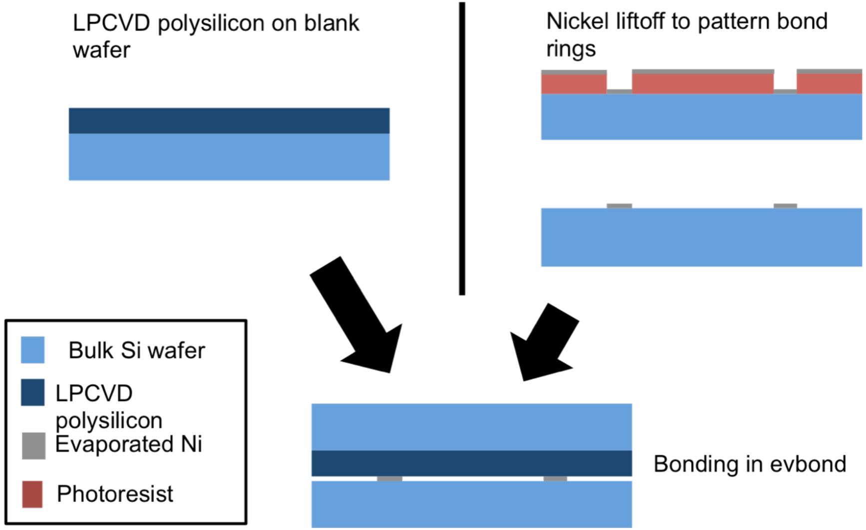
Variables and Experimental Design (Factorial)

Temperature	Force	Bonding ring fill factor
300°C	3340 N	Unpatterned
350°C	1660 N	75%
450°C	1120 N	50%
	540 N	25%
	525 N	10%

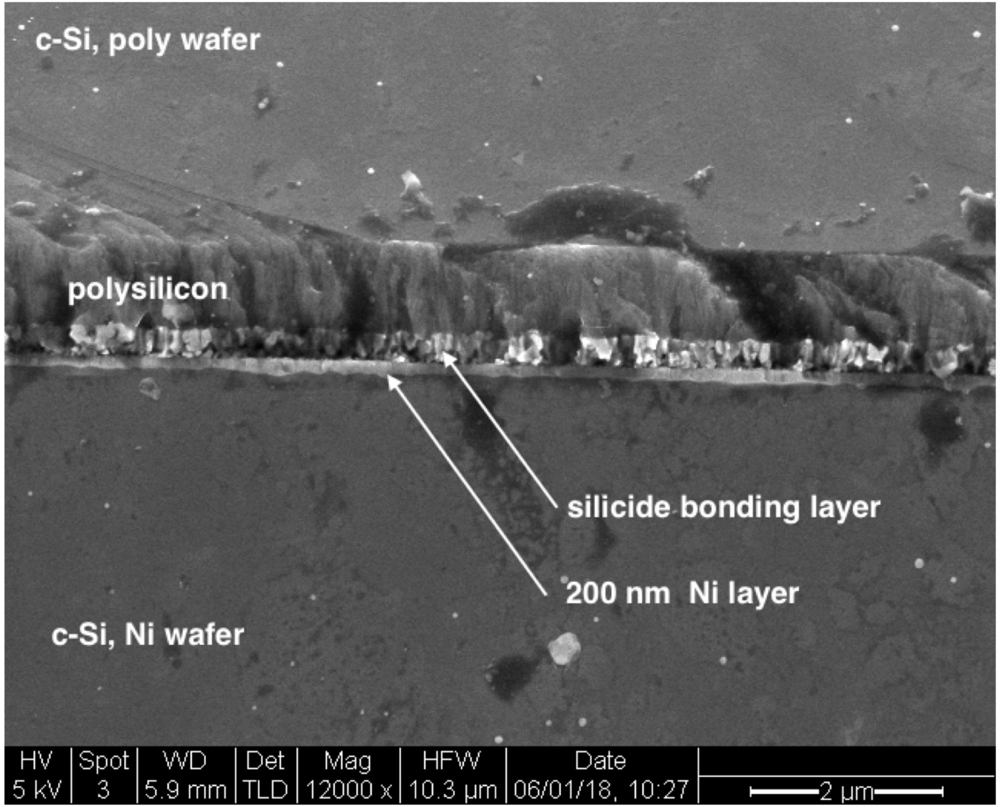
- Varied bonding area, scaled force to keep bonding pressure constant
- Pruned experiments that were likely to fail: if bond fails entirely, little reason to try lower force, lower temperature, lower area

Fabrication flow for patterned bonds

- Polysilicon wafer: LPCVD 1-2 µm polysilicon at 620°C, unpatterned
- Ni wafer: 10 nm Ti/150 nm Ni evaporated and patterned (Heidelberg) by liftoff
- Pre-bond clean and oxide etch (critical step for bonding):
    - 5:1 water:29% ammonium hydroxide for 5 min to strip NiO from Ni wafer
    - 50:1 HF for 1 minute to strip SiO_2 from polysilicon wafer
- Bond in evbond



SEM of nickel silicide wafer bond



Cross section of cleaved bonded wafer pair

Nickel silicide bond is visible

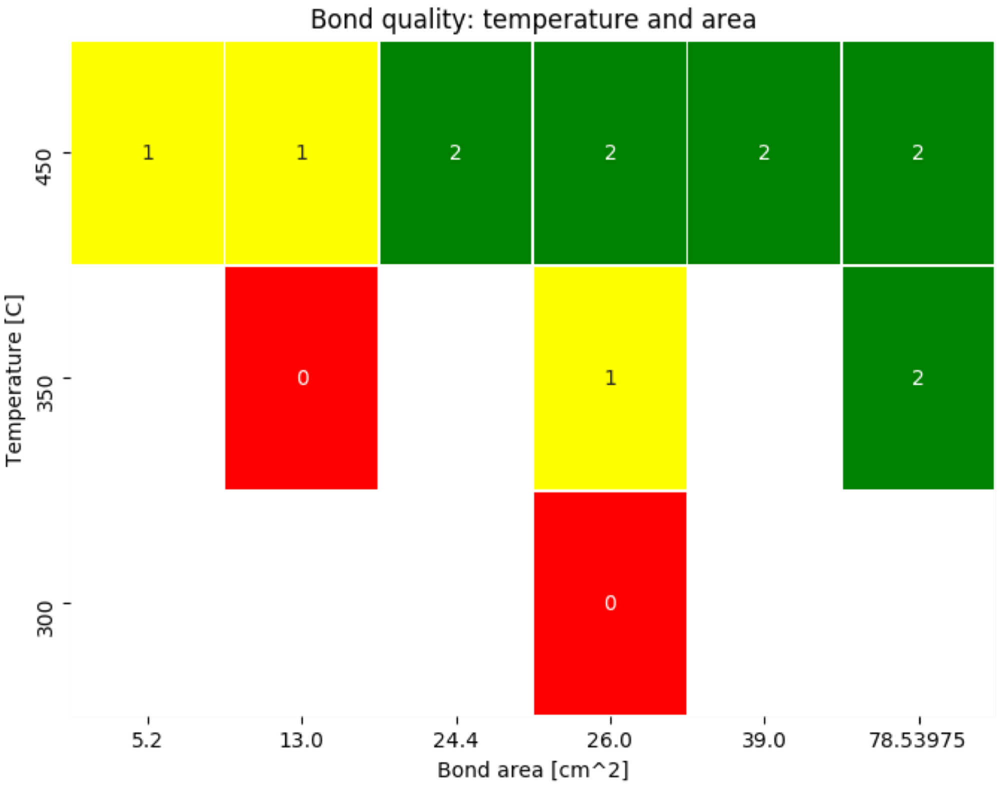
Actual polysilicon thickness around 1.5 µm

Nickel silicide appears to extend ~250 nm into polysilicon layer

Wafer Saw and Razor Blade Testing Methodology

- Qualitatively assessed bond quality
- Dicing or cleaving wafer
  - Wafers that are well bonded should stay together
- Razor blade test: insert razor blade into bonding interface to separate pieces
  - Lousy bond → pieces should pop apart cleanly
  - Good bond → break off bits of silicon
- Assigned numerical scores for bond strength/quality
  - 2 for good bond, 1 for moderate quality bond, 0 for no bond

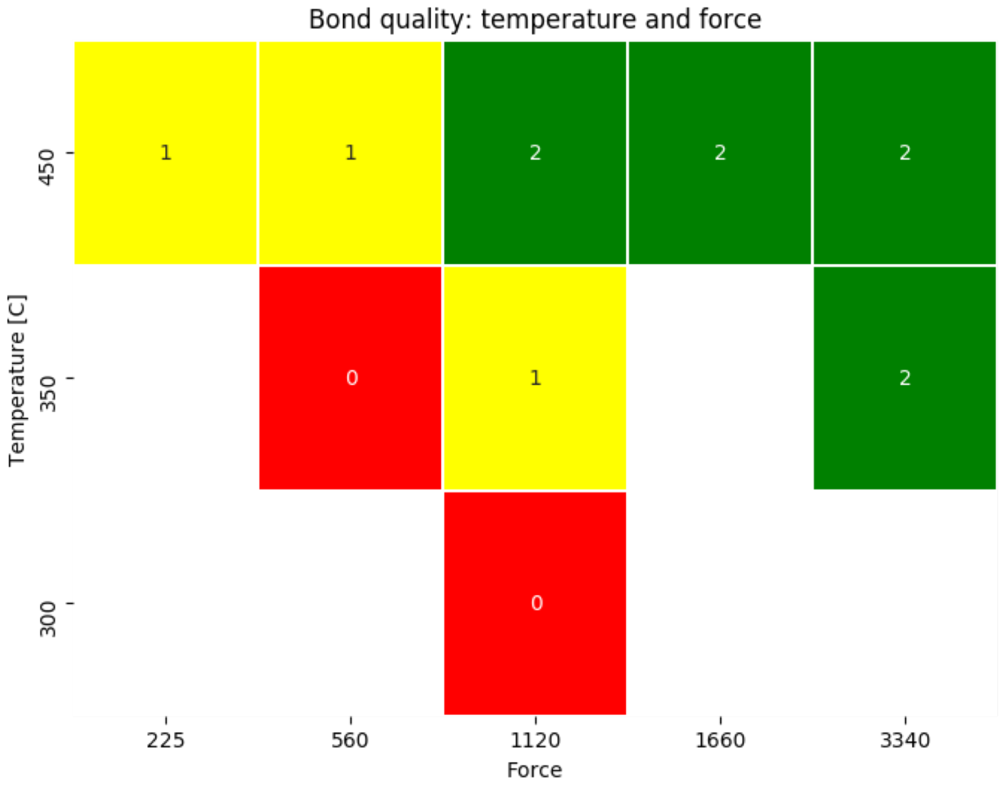
Dependence on temperature and area



Higher temperatures with larger bonding areas produce better results

(2 is good, 1 is moderate quality, 0 is no bond)

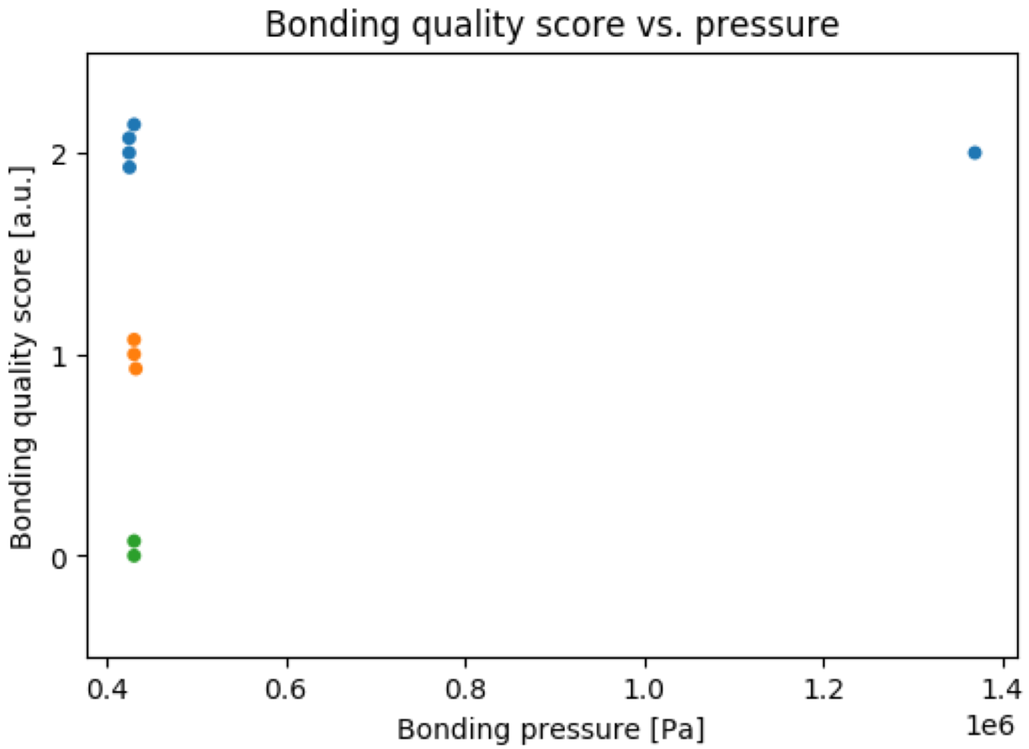
Dependence on force and temperature



Higher temperatures and higher bonding forces result in better bond quality

(2 is good, 1 is moderate quality, 0 is no bond)

Qualitative testing trends - pressure

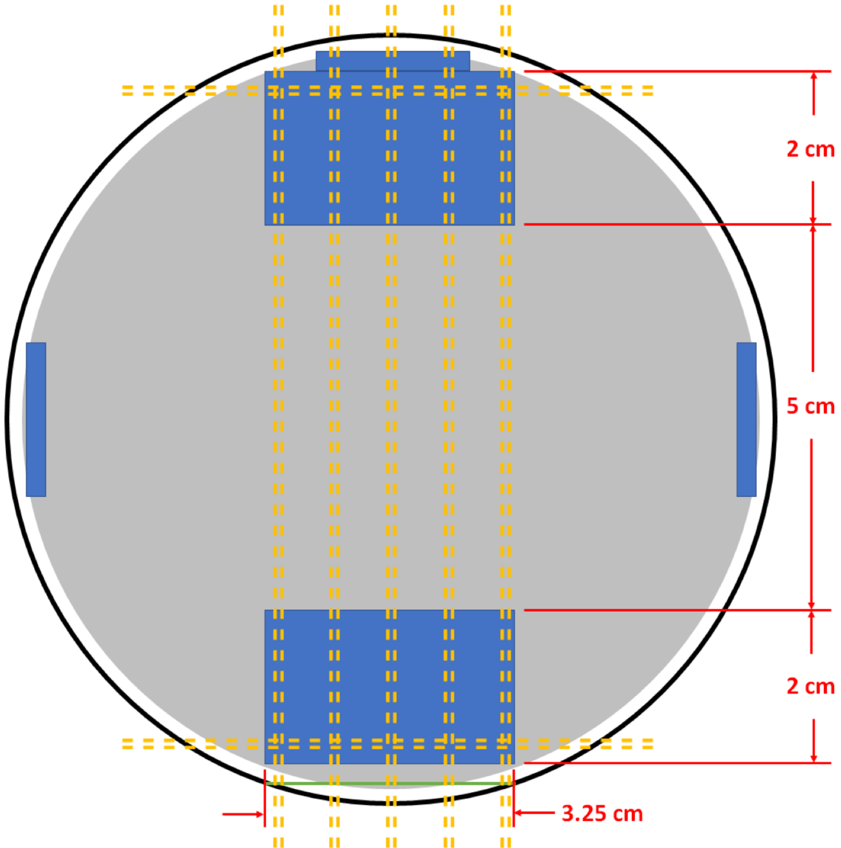


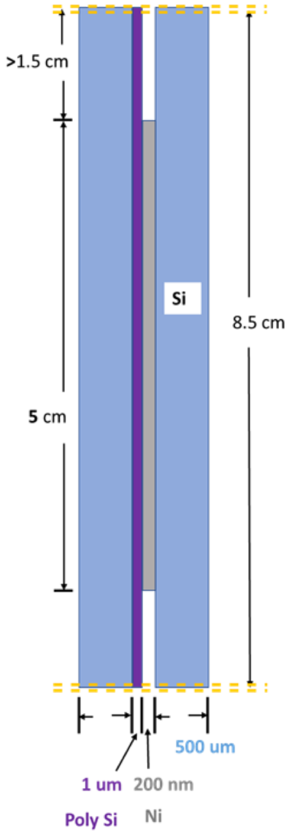
Bond pressure defined as force / (nickel pattern area)

Bond quality has no dependence on pressure

Takeaway: if you scale area, don’t scale pressure, use the max force you can

Double Cantilever Beam sample fabrication



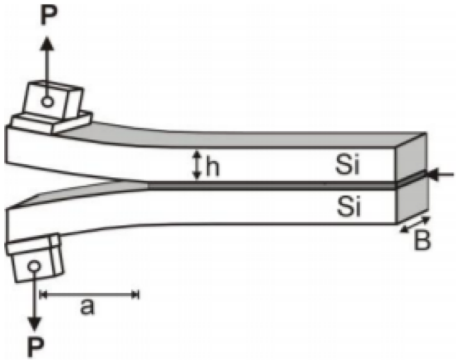


Bonded for 40 minutes at max force (3340 N)

Diced on DISCO wafersaw

Stanford University

Double Cantilever Beam testing methodology



$$G = \frac{P^2}{2B}\frac{dC}{da}$$

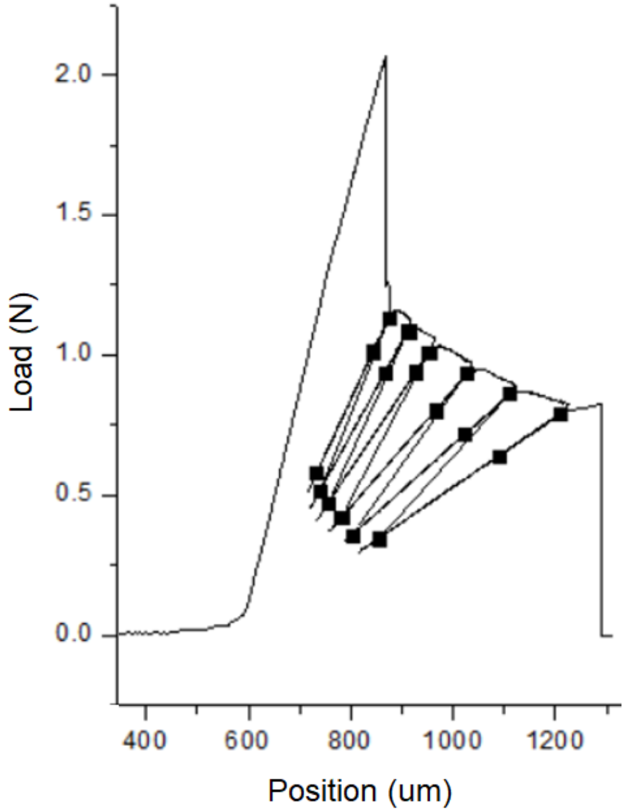
P: load, C: Compliance, a: crack length

$$\frac{\Delta}{2} = \frac{Pa^3}{3EI} \qquad I = \frac{Bh^3}{12} \qquad C_{beam} = \frac{\Delta}{P} = \frac{8a^3}{Bh^3E}$$

E: Young's modulus, I: moment of inertia

Delamination Energy: $\boldsymbol{G = \frac{12P^2a^2}{Bh^3E}}$

Double Cantilever Beam tensile testing results



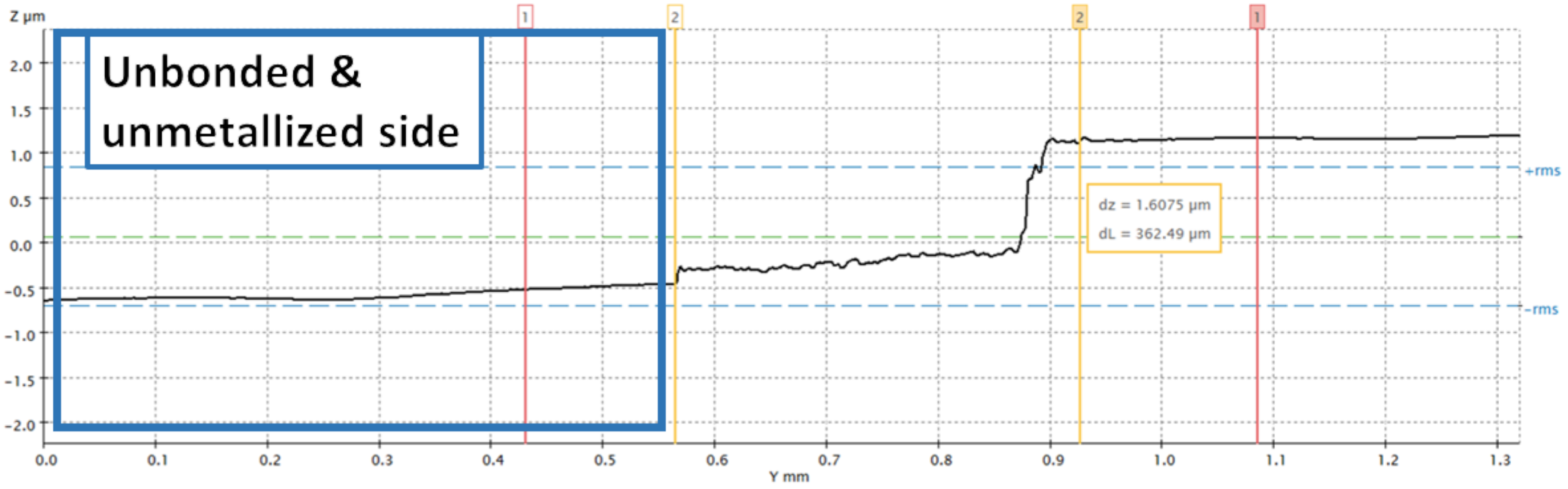
High Temperature (450°C)

You have selected 18 points.

Gc	standard deviation
3.66686	0.05428

crack length	Pc	Gc	C
18.43289	1.1442	3.57149	253.83535
19.63161	1.0947	3.6997	305.59623
20.88074	1.0202	3.62753	366.5594
22.86294	0.9373	3.66034	479.10307
24.91224	0.8689	3.72547	617.51138
27.13807	0.7976	3.71664	795.52525

Double Cantilever Beam sample surface analysis

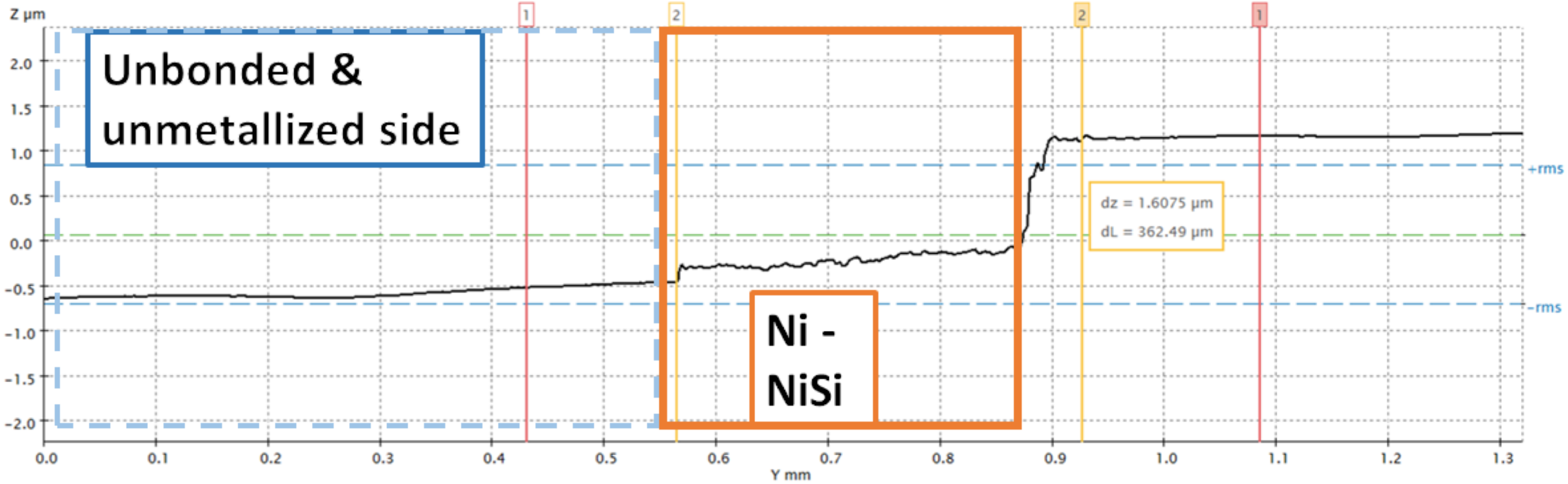


High temperature specimen - Ni side down.

Clear crack propagation through the Ni (~150 nm) - NiSi (~250 nm) - polySi interfaces

Catastrophic failure appears in polySi/Si interface - very flat.

Double Cantilever Beam sample surface analysis



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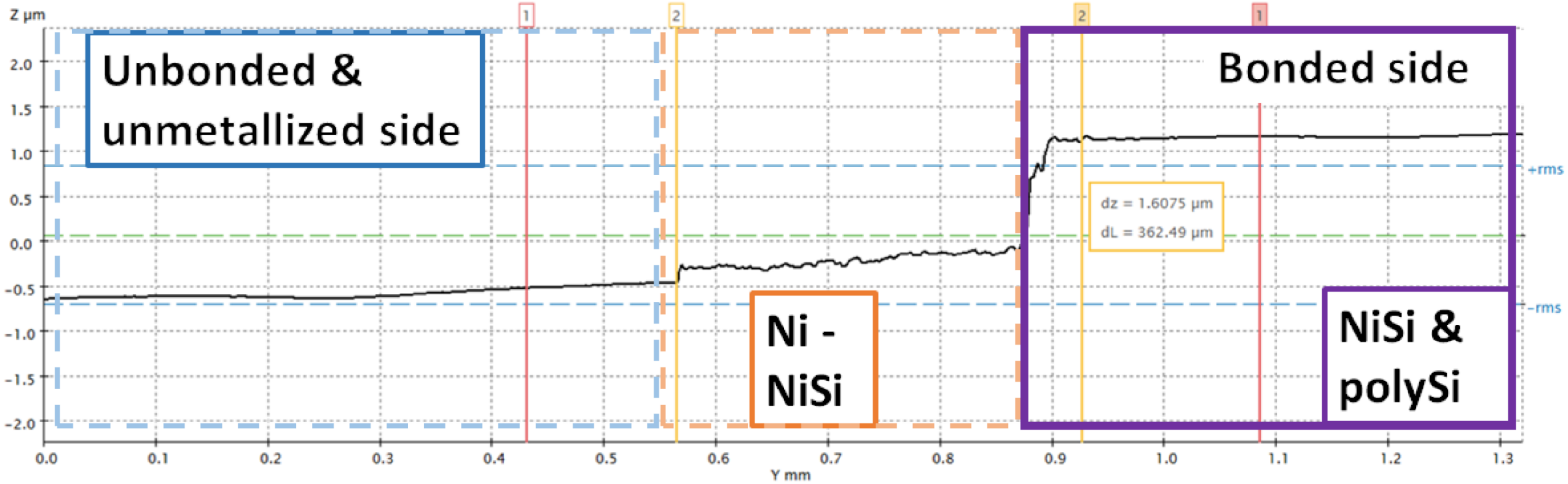

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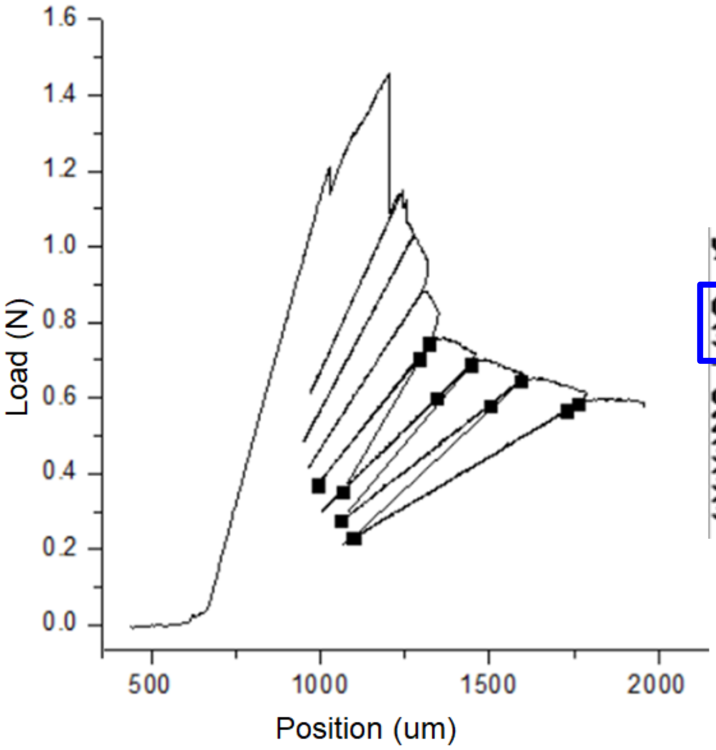


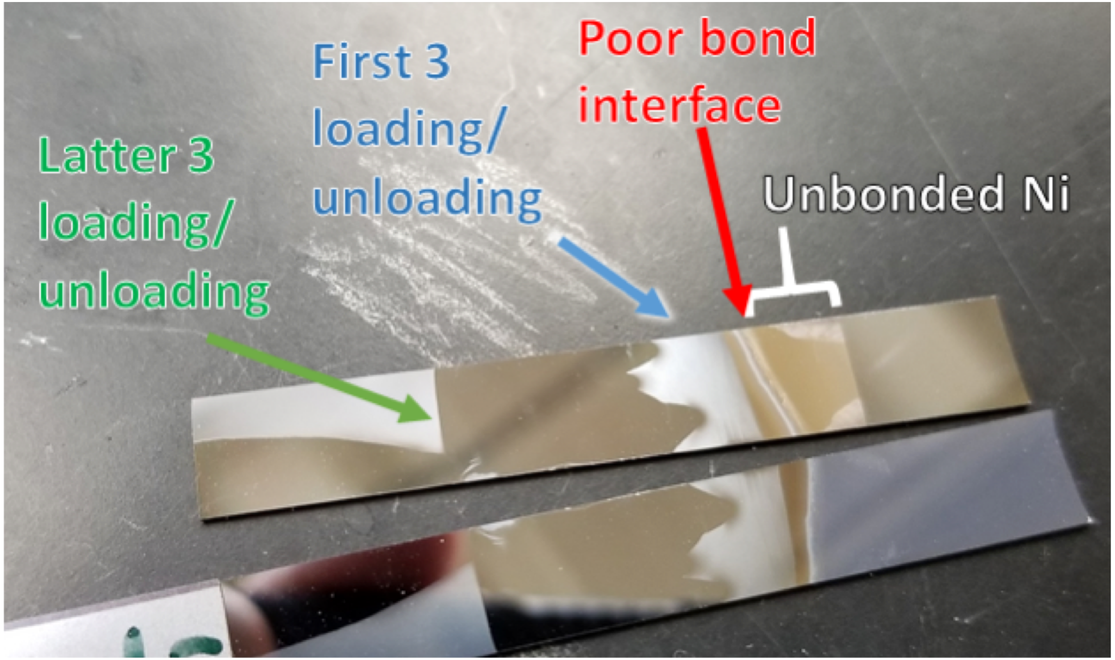
Low Temperature (350°C)

You have selected 12 points.

Gc	standard deviation
3.56295	0.04478

crack length	Pc	Gc	C
29.6412	0.7618	3.51697	903.24722
31.96991	0.7077	3.52453	1130.26252
34.66996	0.6625	3.626	1437.67267
37.91792	0.6028	3.58429	1875.68919

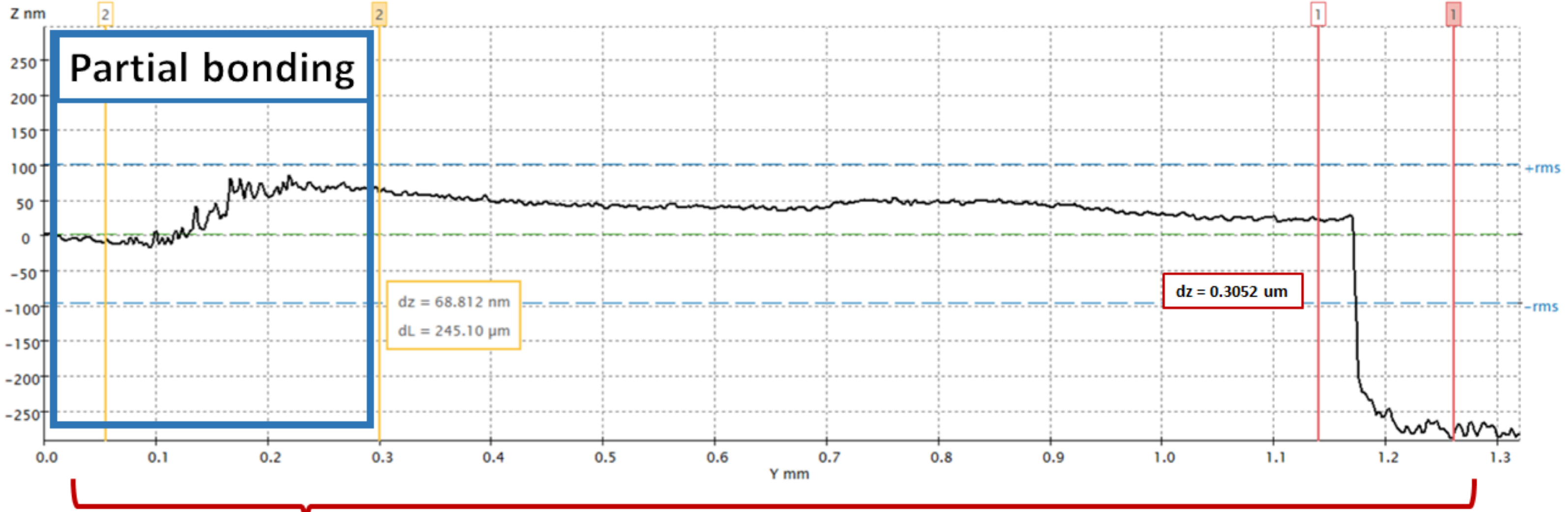
Double Cantilever Beam sample surface analysis

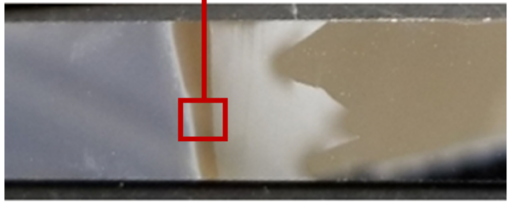


Low temperature specimen

- Incomplete bonding
- Multiple crack propagation interfaces

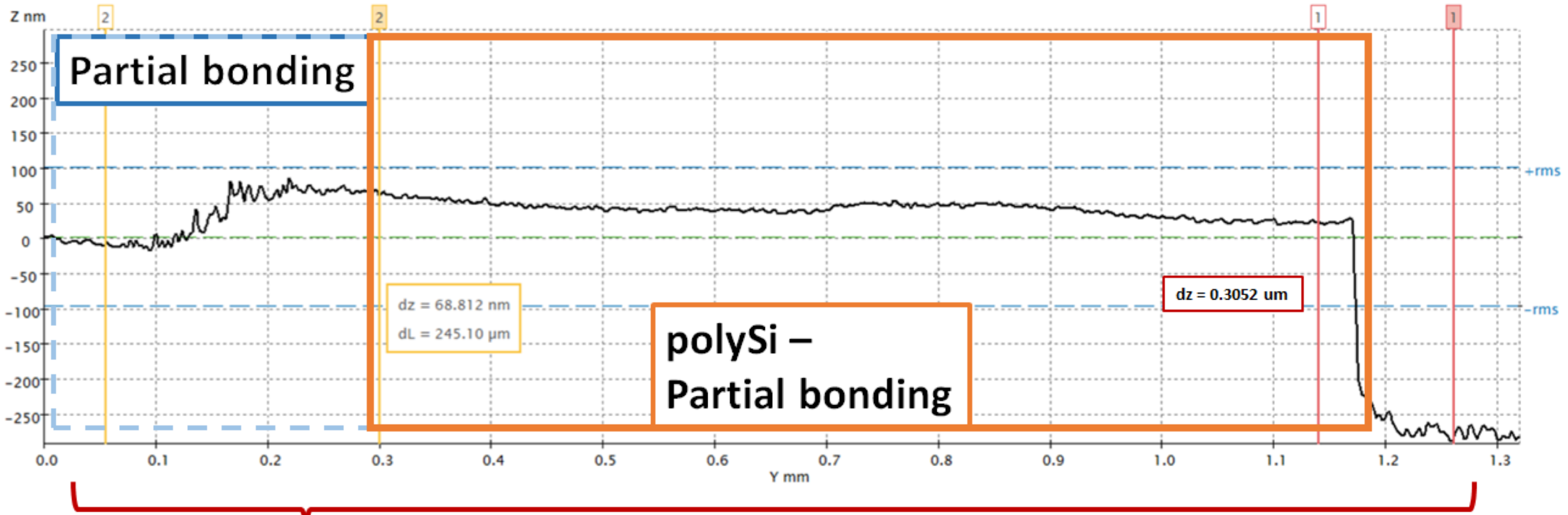
Double Cantilever Beam sample surface analysis

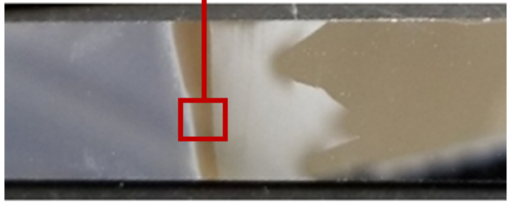




Low temperature specimen - poor bonding and first interface. PolySi side down.

Double Cantilever Beam sample surface analysis





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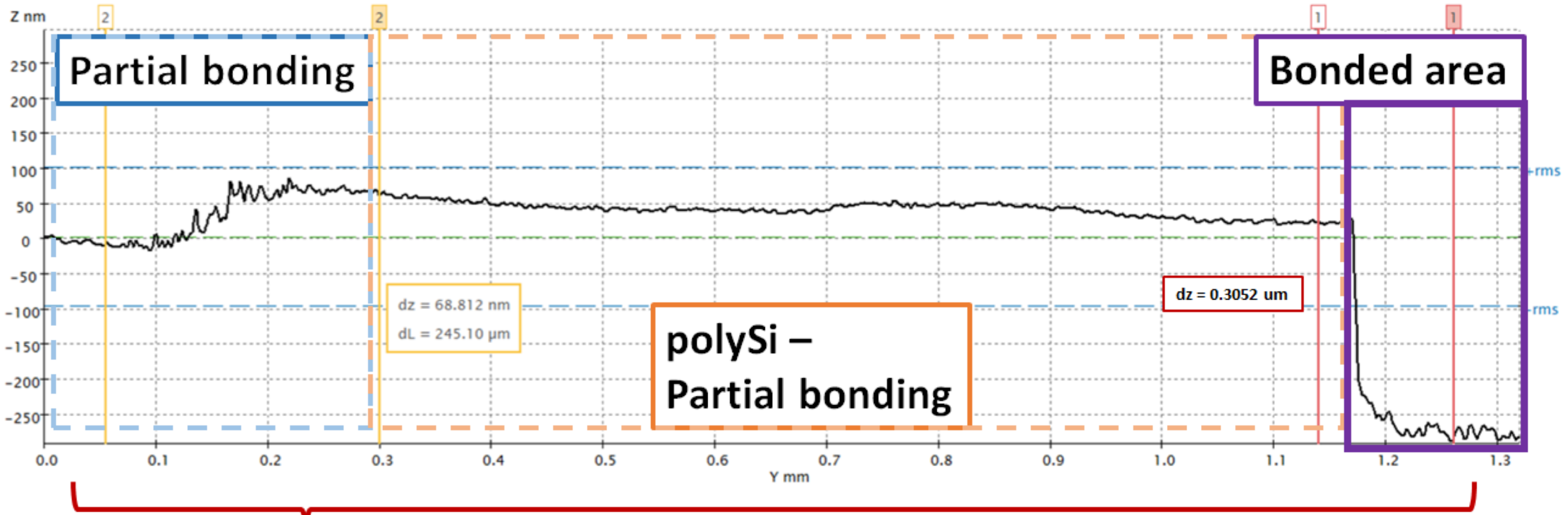

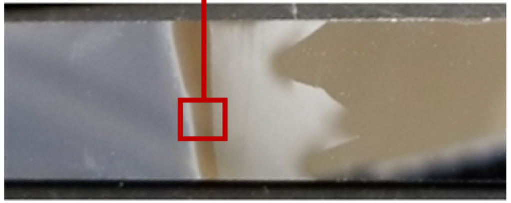

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Conclusions

- Pre-clean and oxide etch is of utmost importance

- NiSi formation is straightforward at 450°C and forms a strong enough bond through solid state diffusion that catastrophic failure occurs in delamination of the polysilicon-Si interface.
  - Would be useful to perform DCB testing on other bonding forms to verify whether the NiSi bond is in fact brittle or if it is just polySi/Si
  - Dauskardt: “metal joints are typically in the range of 100-1000 J/m^2

- Use highest temperature and bonding force that is compatible with your process

Future work

- Additional double cantilever beam delamination testing
  - More on NiSi to verify delamination behavior
  - More bonding techniques to determine if brittleness is because of Si

- SEM/XPS of DCB samples to verify

- Application specific testing
  - Hermiticity
  - Thermal shock and cycling, Annealing effects
  - Conductivity
  - Cesium vapor compatibility

- Additional materials systems: Cobalt, Titanium, Platinum ($)

Acknowledgements

- Stanford Nanofabrication Facility
  - Mahnaz Mansourpour, Dr. Xiaoqing Xu, Uli Thumser, Maurice Stevens, Prof. Roger Howe, Dr. Mary Tang

- Dr. J Provine - external mentor

- Dr. Mark Zdeblick - additional advice

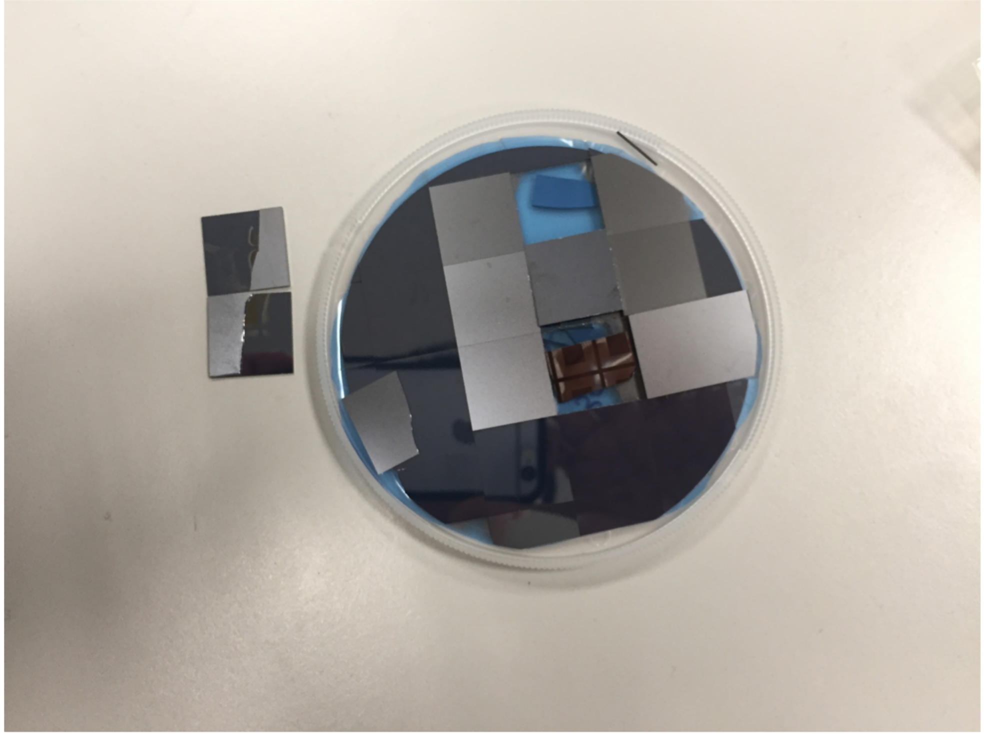
- Charmaine Chia - SEM operation

- Prof. Reinhold Dauskardt and Yichaun Ding - DCB testing and analysis

Questions?

Backup slides

Example of moderate quality bond



Bonded pair somewhat intact after dicing

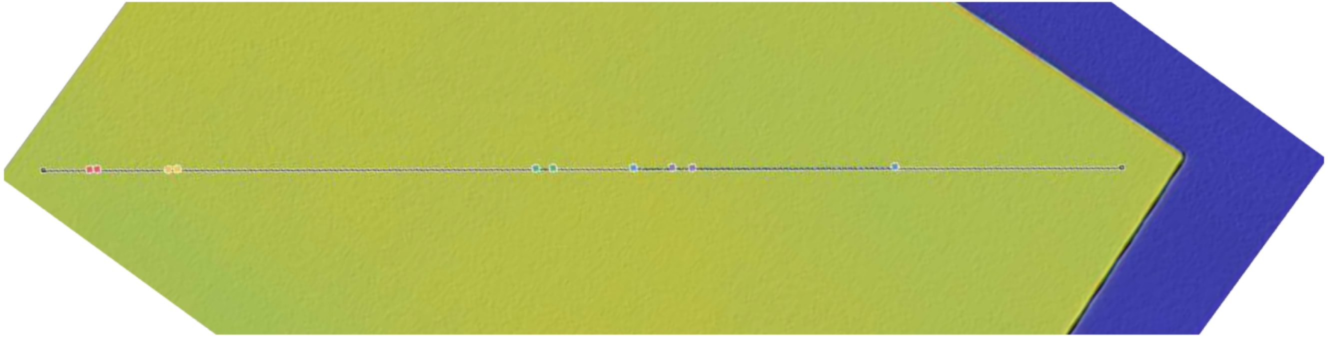
Some pieces could be separated with razor blade, others showed signs of bonding

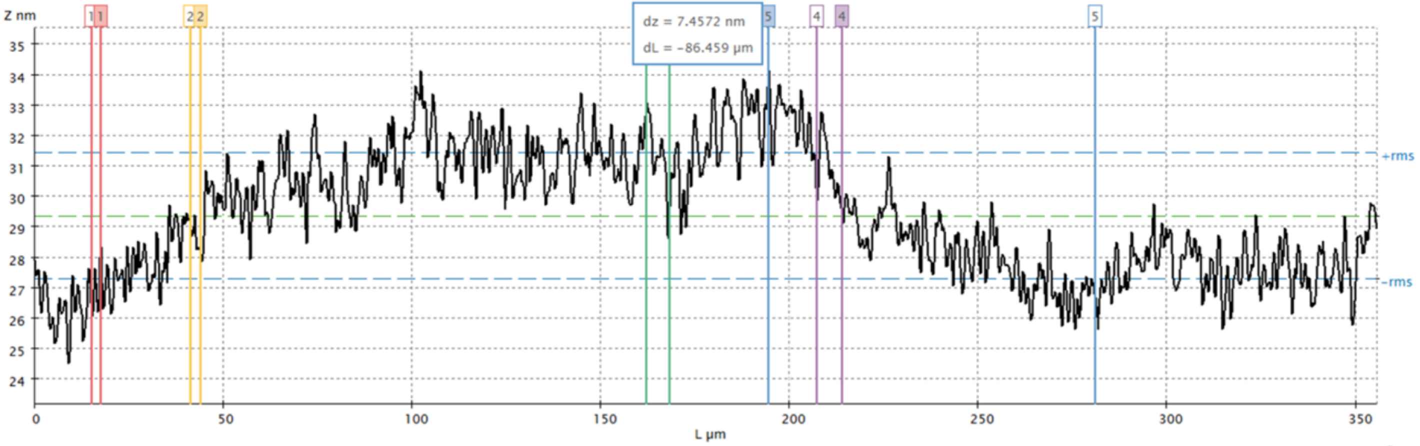
Example of good quality bond

Almost entire wafer stayed together during dicing

Razor blade test chipped fragments off of samples rather than separated them

Surface Roughness





RMS: 2 nm

Solid State Diffusion

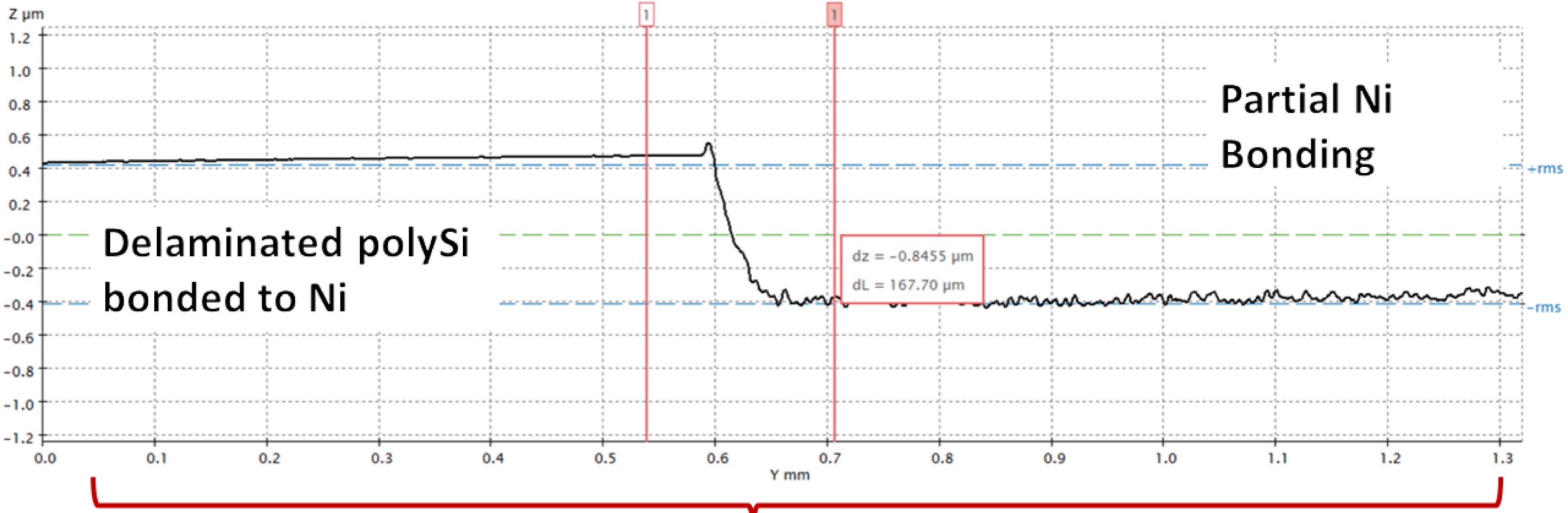
$$\frac{c(x,t)-c_0}{c_s-c_0} = 1 - erf\left(\frac{x}{2\sqrt{D\cdot t}}\right)$$ fraction/cm³

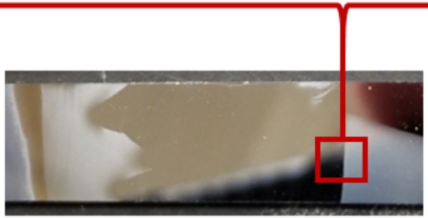
$$D_{Ni,Si} = 2 \times 10^{-3}\, exp\left(-\frac{0.47\ eV}{k_B\ T}\right)\ cm^2/s$$

Referenced from: Weber, E.R. Transition Metals in Silicon. *Journal of Applied Physics.* A30, 1-22. (1982)

- At 40 minutes bonding time and 450ºC, simple calculation yields that Ni will be 10% of the atomic fraction at a depth of **1.25 mm**.
- This is very deep - likely that there are more complex diffusivity calculations that could be made.
- Additionally, the NiSi reaction is probably blocking further diffusion just as an oxide layer might.

Double Cantilever Beam sample surface analysis





Low Temperature specimen:
second interface