Yielding and plastic slip in ZnO

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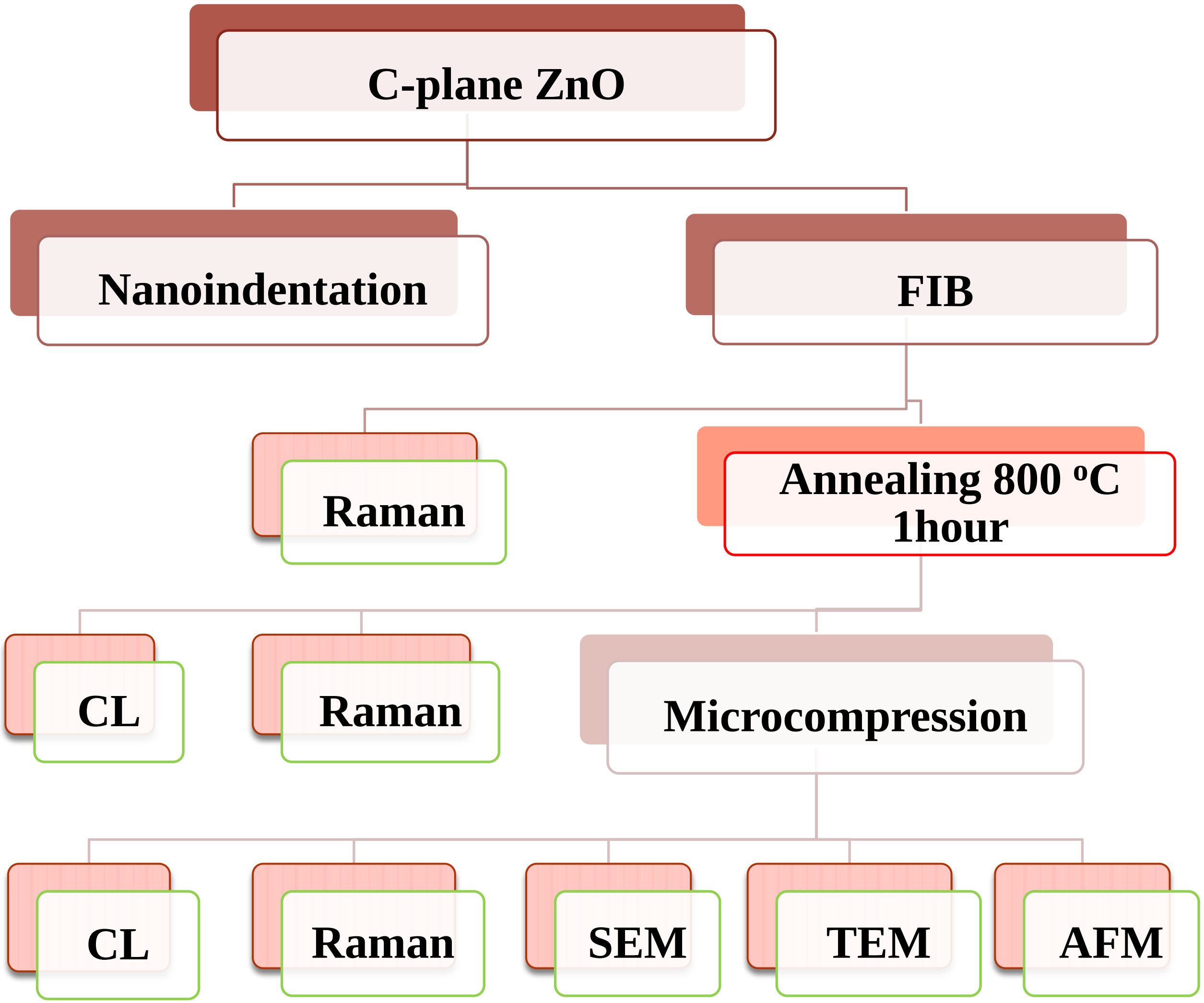
Outline

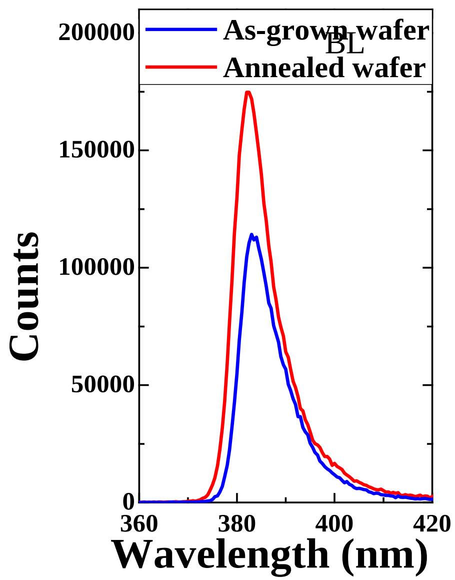
- Residual stress and defect density
- Nanoindentation testing
- Microcompression


C-plane ZnO
Nanoindentation
FIB
Raman
Annealing 800 ºC 1hour
CL
Raman
Microcompression
CL
Raman
SEM
TEM
AFM

The mechanical properties of ZnO

	Structure	Method	E (GPa)	H (GPa)	Slip system	Reference
Polycrystalline	Bulk	Calculation	120	-	-	Shein et al. [5]
		Experiment	140	-	-	Shein et al. [5]
Single crystalline	Bulk	Nanoindentation	123 *	5.1	-	Present work
			111	5	Pyramidal	Bradby et al. [4]
			112	5.4	Pyramidal	Jain et al. [15]
	Micropillar	Microcompression	118	-	Pyramidal	Present work
	Nanorod	Nanoindentation	63	9.7	-	Yan et al. [9]
	Nanowire	Tension	21	-	-	Desai et al. [20]
			160	-	-	Xu et al. [21]
	Nanobelt	Bending	31.1	2.5	-	Ni et al. [8]
		Bending	51	-	-	Bai et al. [22]

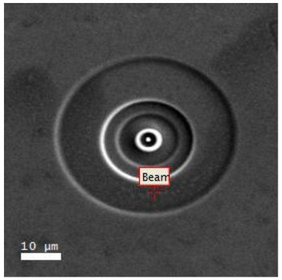
CL – annealed effect



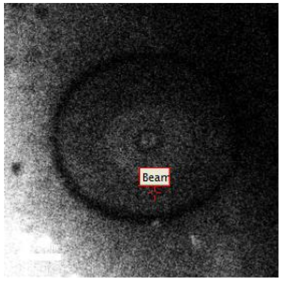
Blue luminescence				
		ISU	A800	
Wavelength	P1	383.1	381.9	
FWHM		4.5	4.8	
Wavelength	P2	388.0	386.6	
FWHM		8.1	8.0	
Intensity		**114538**	**174653**	**1.5 times**

Wave length = 383 nm

Unannealed

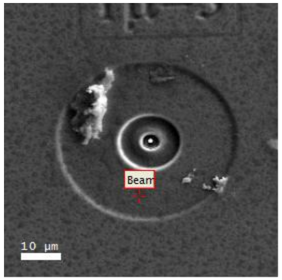


SEM image

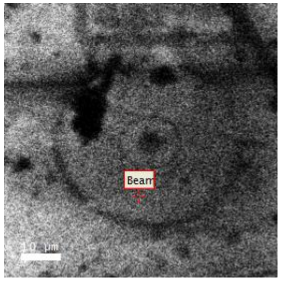


CL image

Annealed 800 ^{o}C

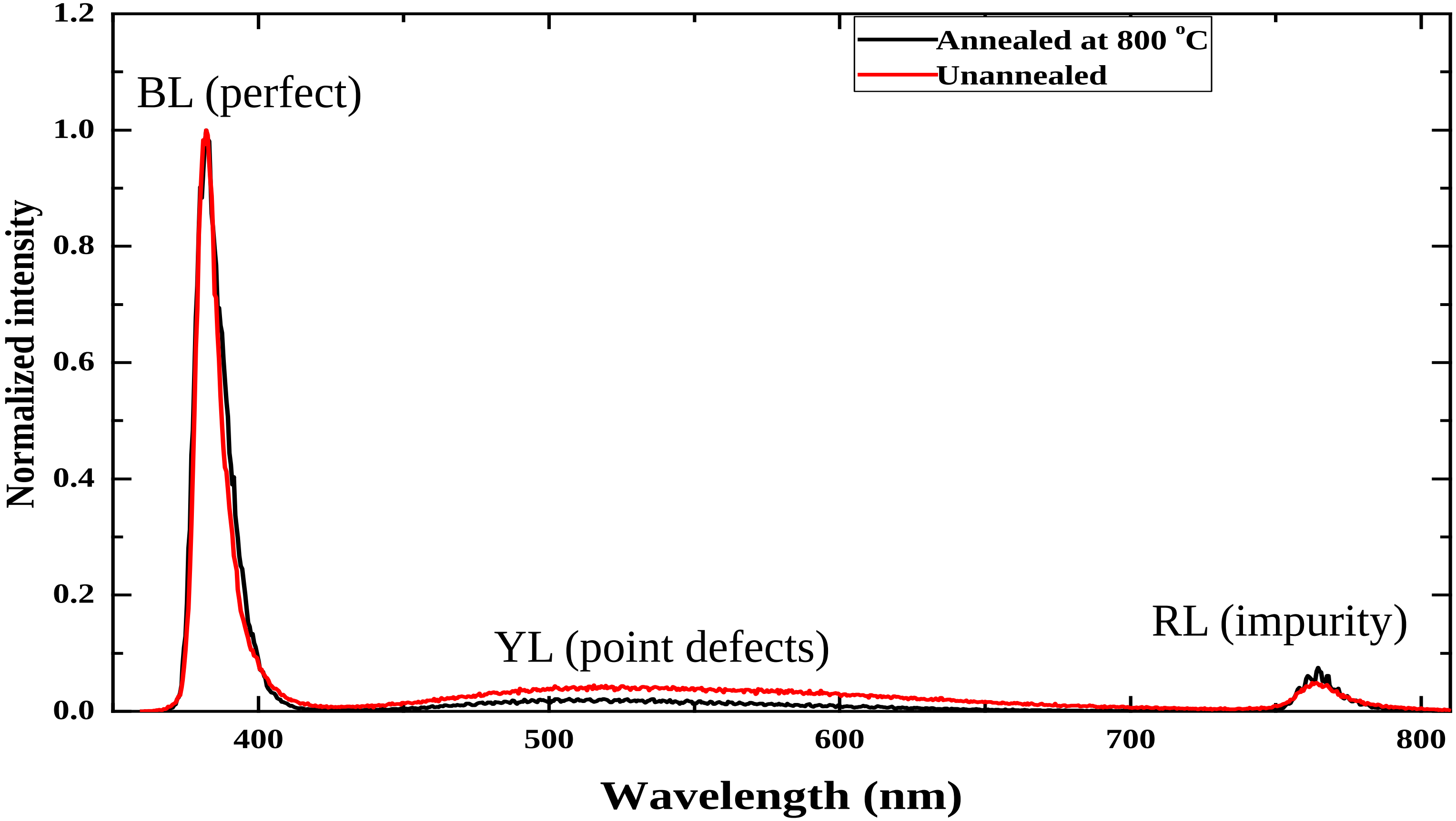


SEM image



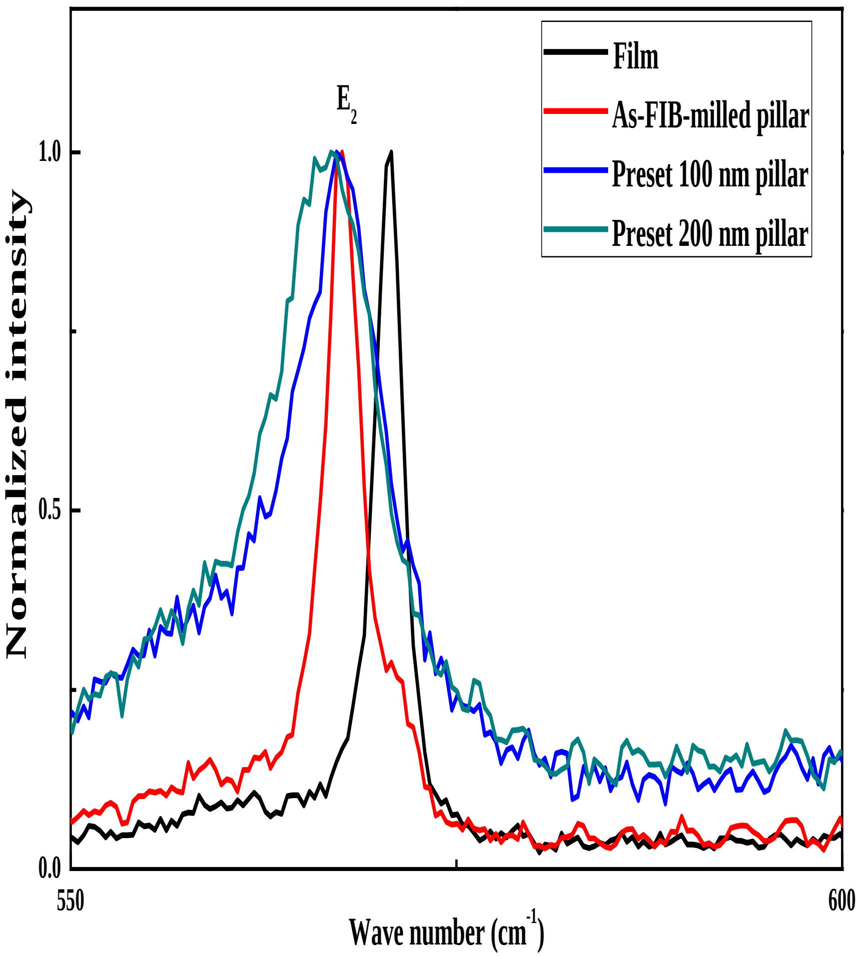
CL image

CL Spectrum

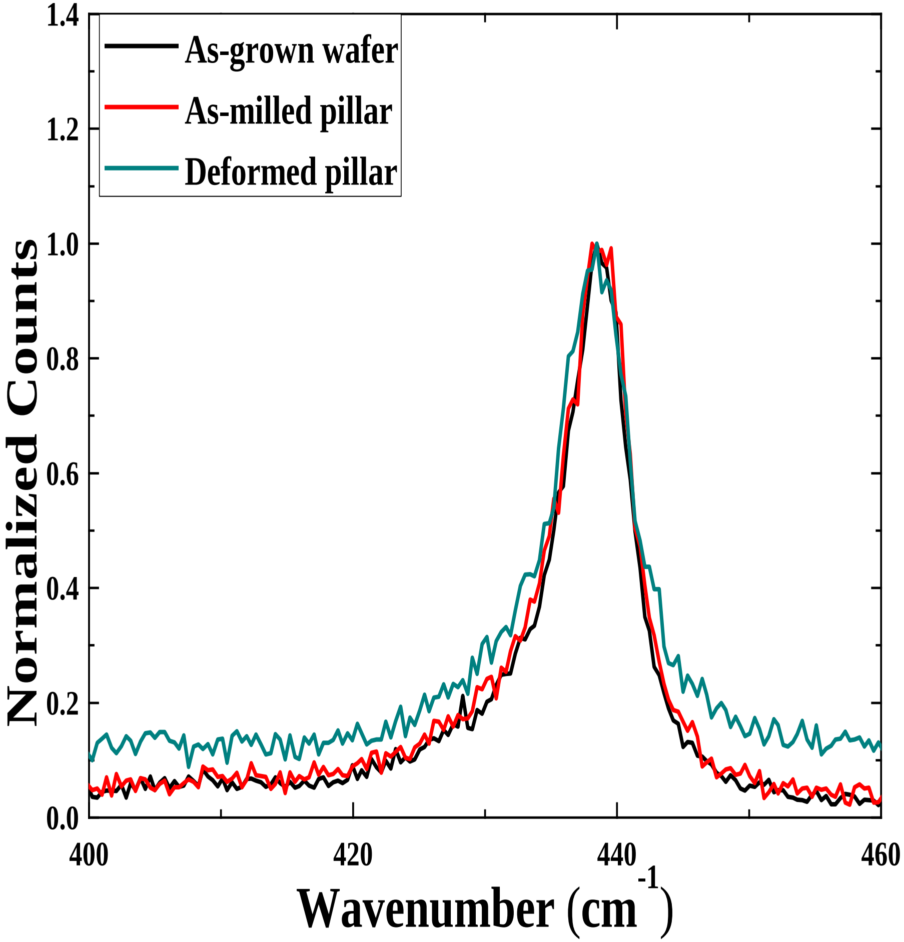


Annealed at 800 °C
Unannealed
BL (perfect)
YL (point defects)
RL (impurity)
Normalized intensity
Wavelength (nm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
800

Raman – residual stress



GaN/Sapphire thin film



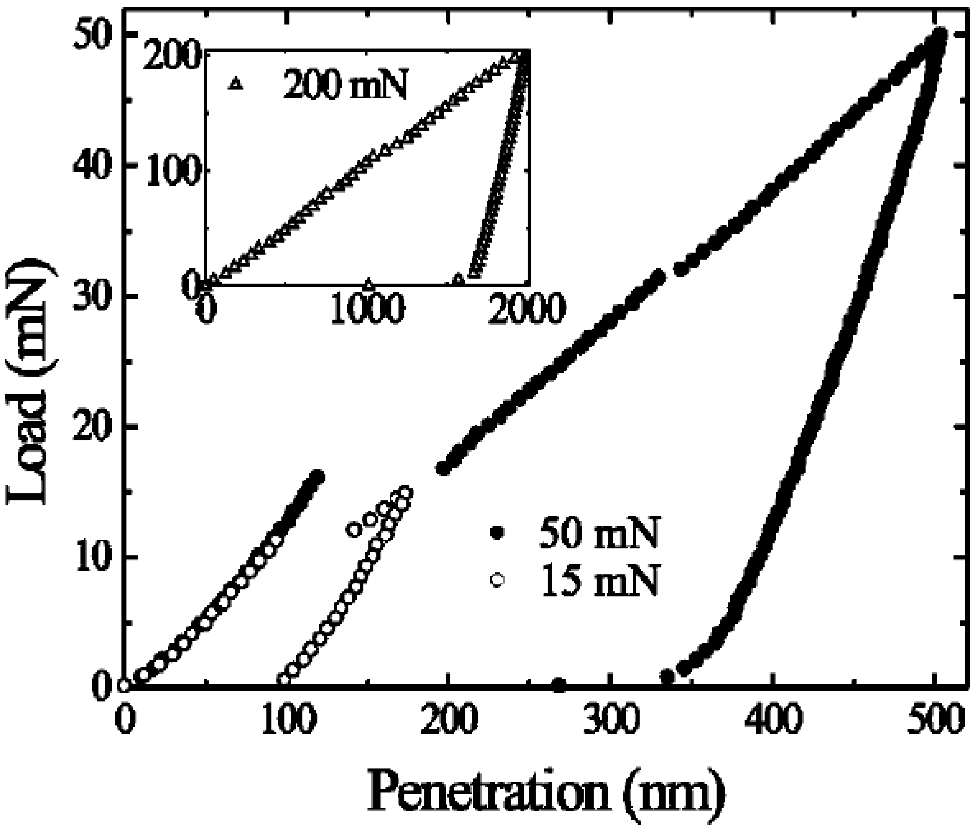
ZnO wafer

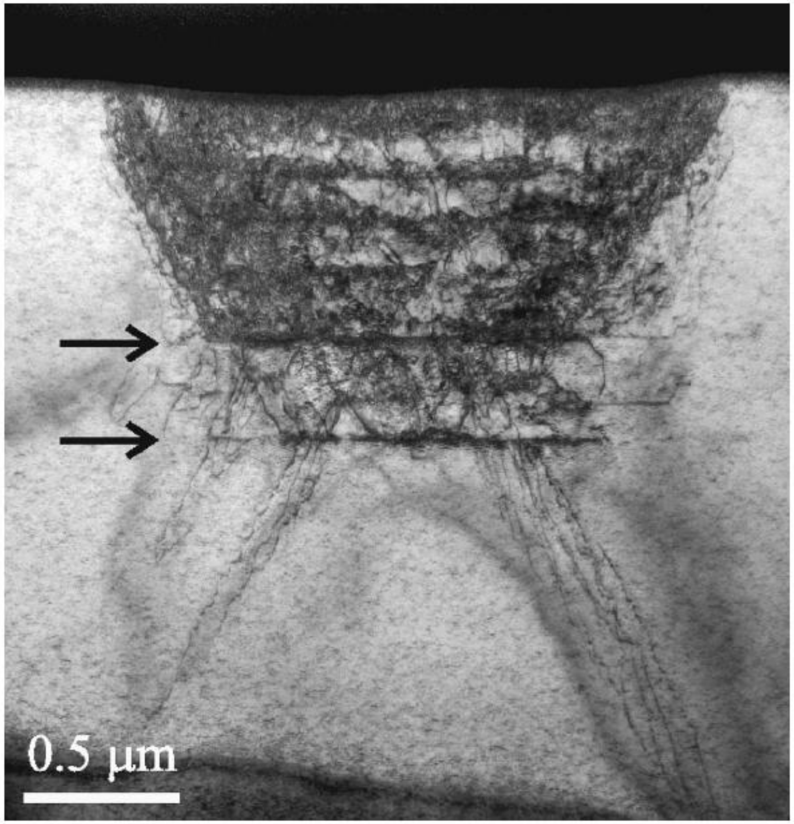
Conclusion

- No residual stress remains in wafer, as-grown pillar and deformed pillar.

- The improved BL intensity in CL spectrum in the annealed wafer was apparently due to the reduction of defect density not residual stress.

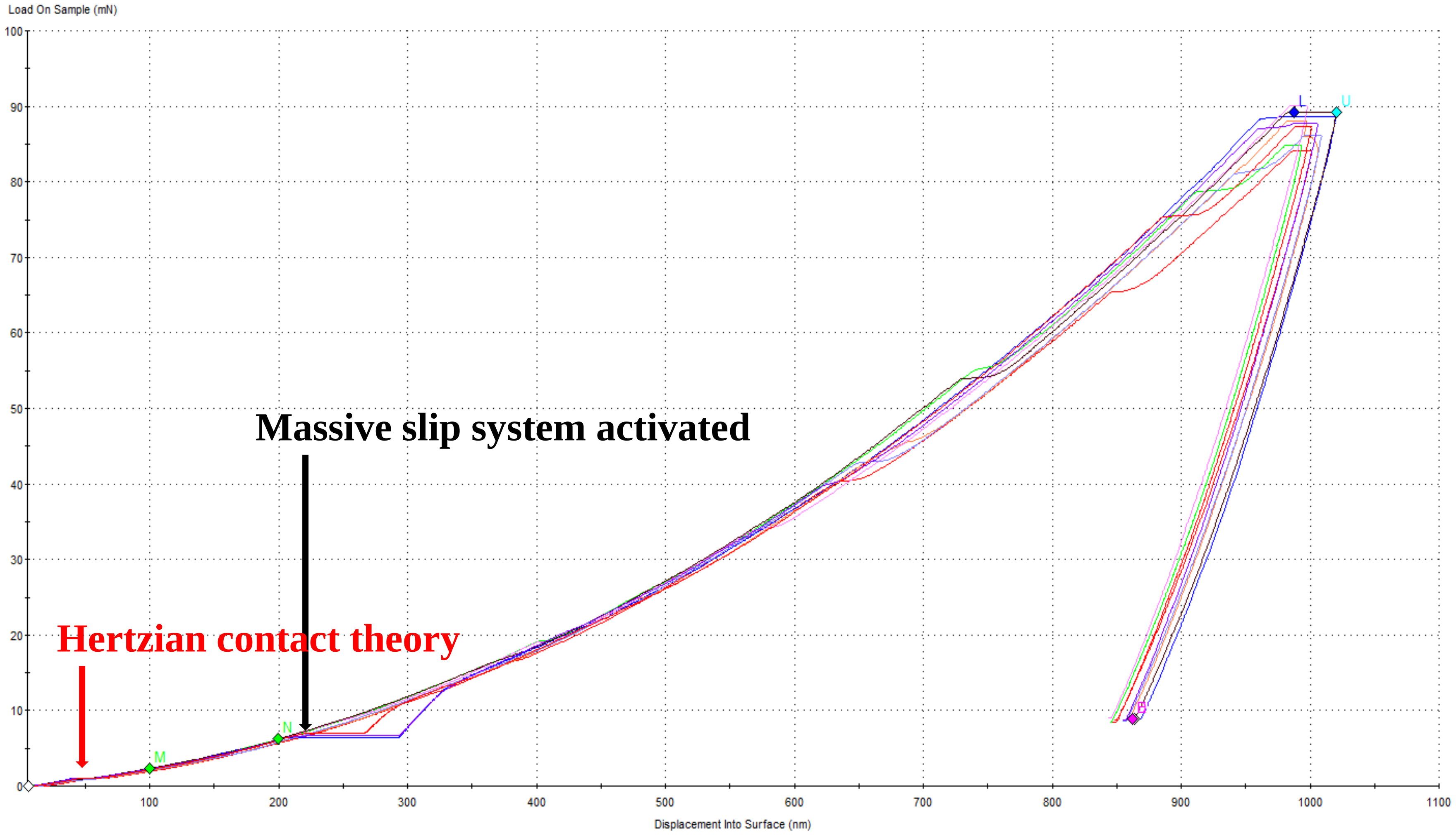
Nanoindentation



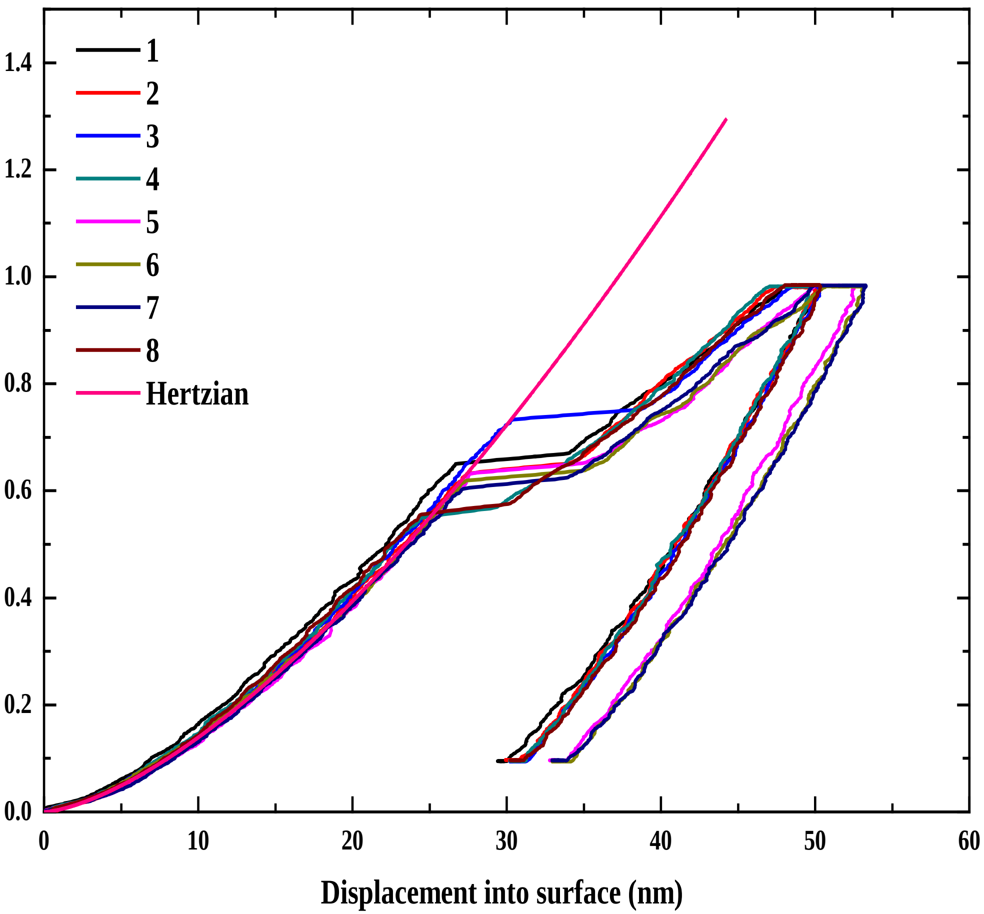


J. E. Bradby et. al, Applied Physics Letter **80** (24), 4537 (2002).

Nanoindentation



Nanoindentation of as-grown ZnO



Hertzian contact theory

- For shallow displacement < 100 nm

$$P = \frac{4}{3} E_r \sqrt{R}$$

$$E_r = \left(\frac{(1-\nu_t^2)}{E_t} + \frac{(1-\nu_s^2)}{E_s} \right)^{-1}$$

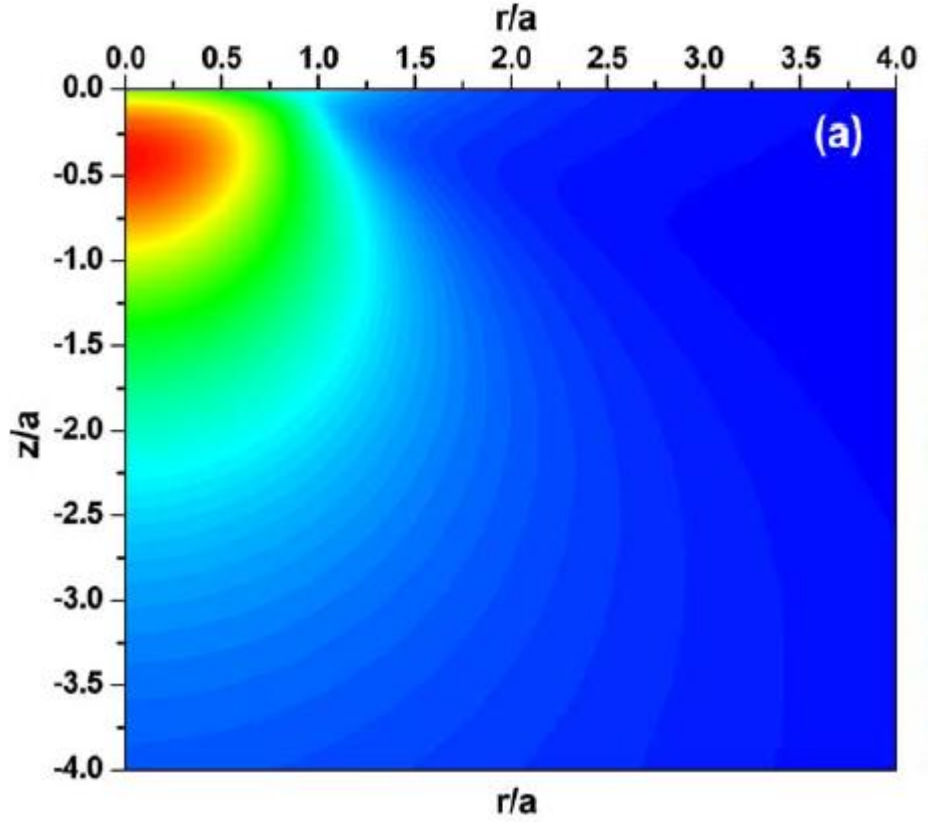
$$A = 22.8 h_c^2 + 1352 h_c$$

R ~600 nm

P = 0.5 mN

W.G. Mao et al., Journal of the Ceramic society 31, (2011).

CRSS

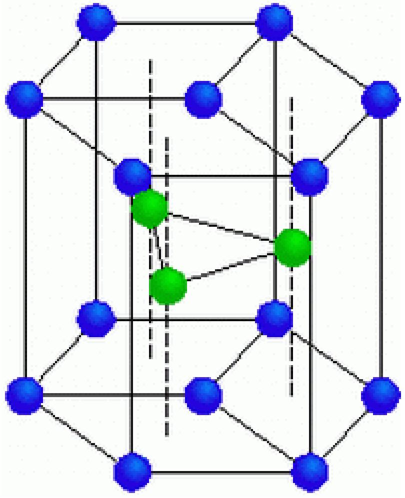


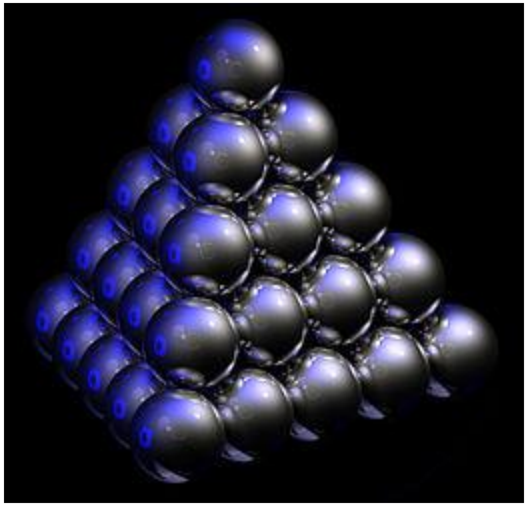
$\sigma_{as\text{-}grown} = P/A = 14.4$ GPa

$\sigma_{annealed} = 14.5$ GPa

W.G. Mao et al., Journal of the Ceramic society 31, (2011).

Slip systems

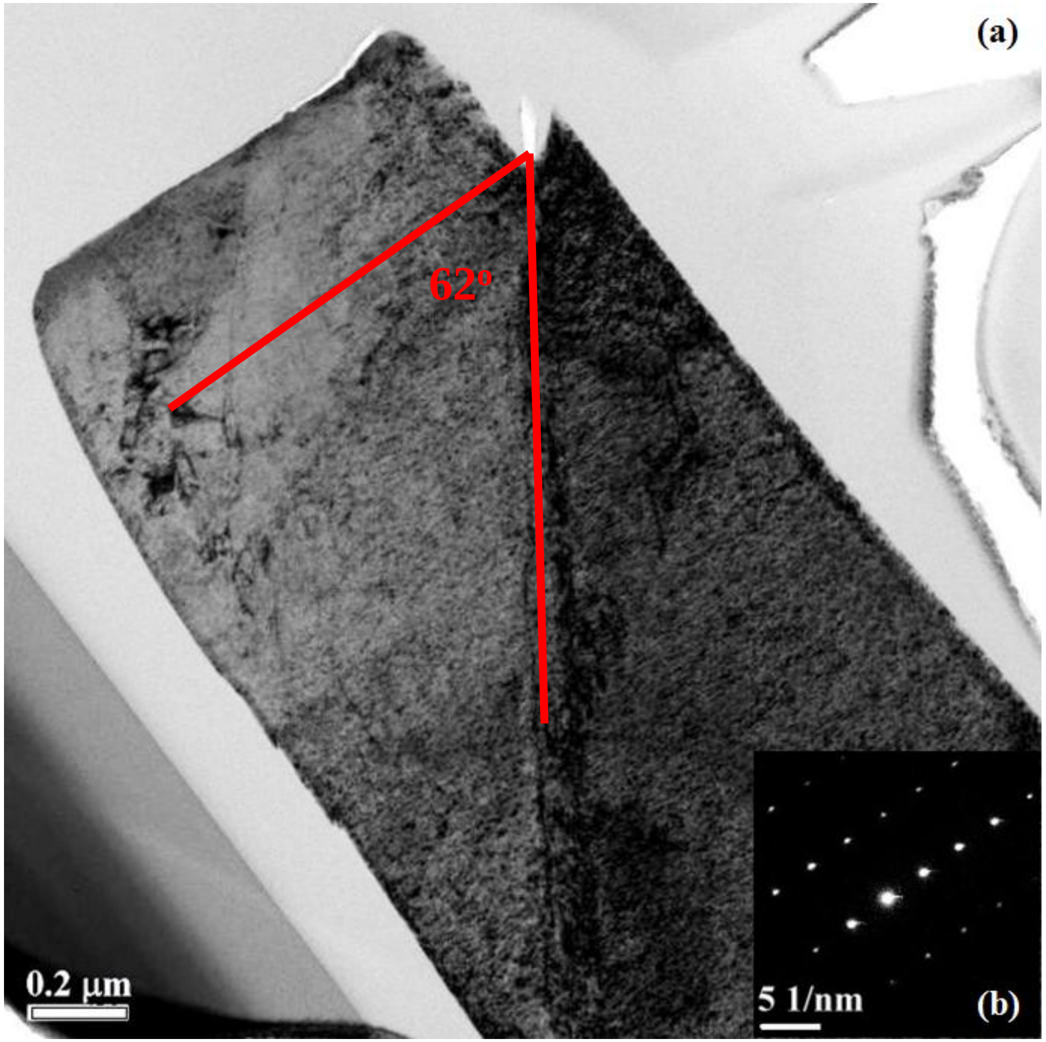




(hkil)	*d*	angle	[uvtw]	angle	Schmid Factor
(10-11)	1.04	62	[-1011]	47	0.34
(10-12)	0.99	43	[-2113]	31	0.38
(2-1-11)	0.924	72	[-2113]	31	0.16
(2-1-12)	0.885	58	[-2112]	17	0.16

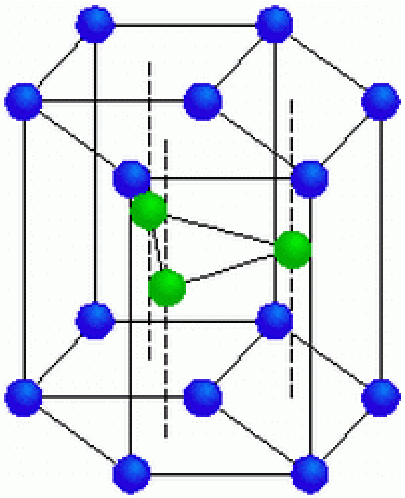
W.G. Mao et al., Journal of the Ceramic society 31, (2011).

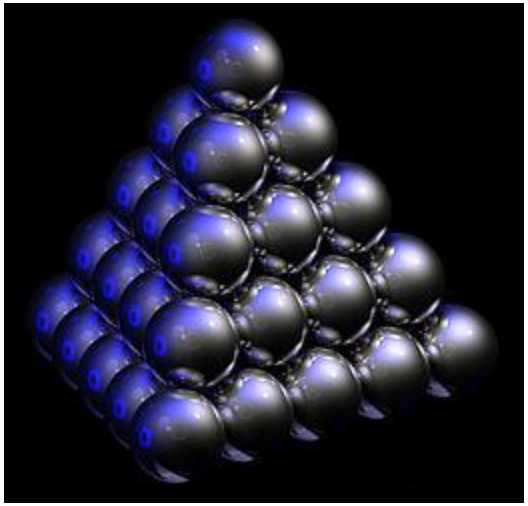
XTEM



Zone axis = [10-10]

Slip systems





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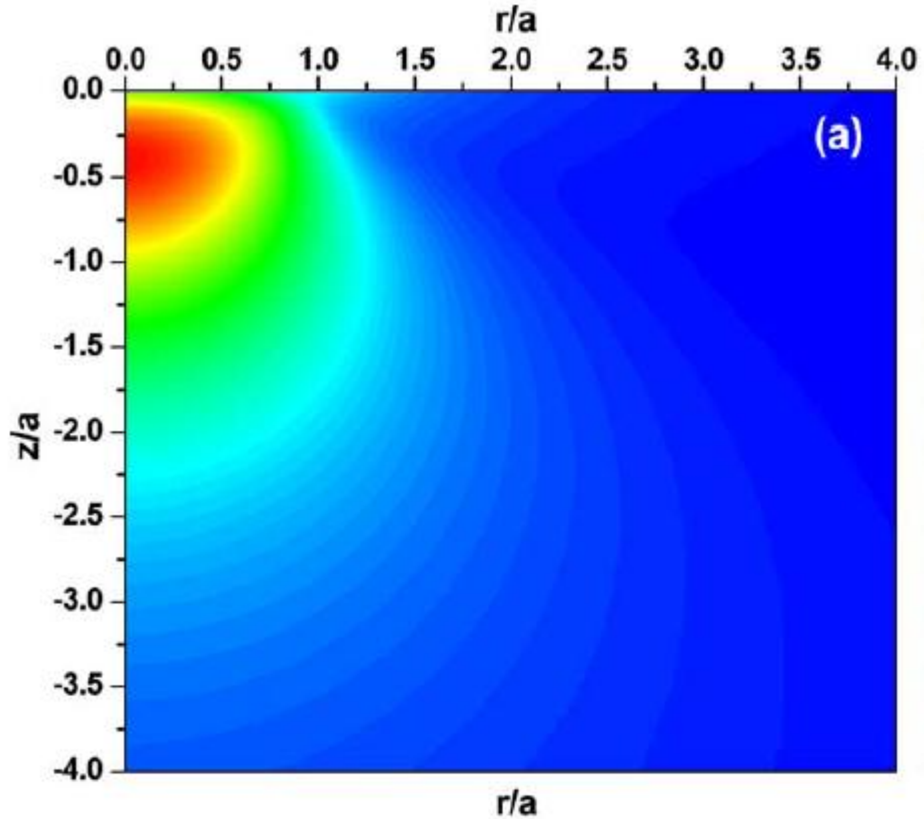
Maximum load



$\sigma_{as\text{-}grown}$ = P/A = 14.4 GPa

$\sigma_{annealed}$ = 14.5 Gpa

$\tau_{max,\ CRSS}$ = 14.4 x 0.34 = 4.9 GPa

at ~1/2 contact radius

$$P_{max} = \left(6PE_r^2 / \pi^3 R^2\right)^{1/3}$$

P_{max} = 16 GPa

$\tau_{max,\ CRSS}$ ~ 0.3 P_{max}

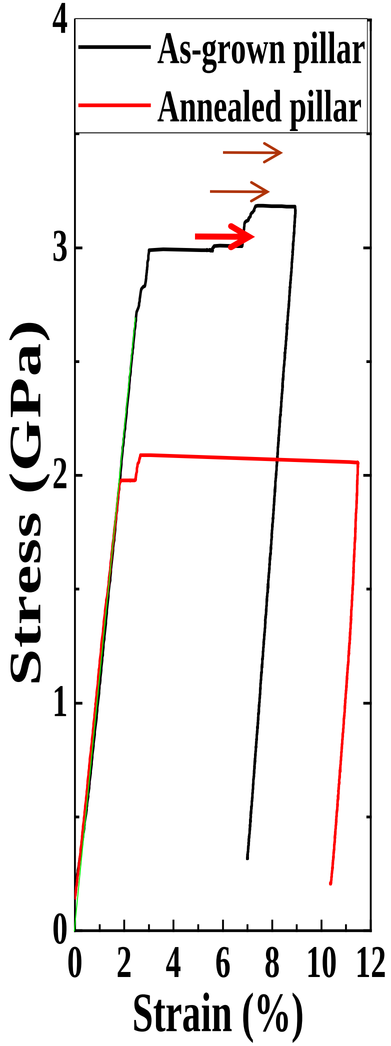
W.G. Mao et al., Journal of the Ceramic society 31, (2011).

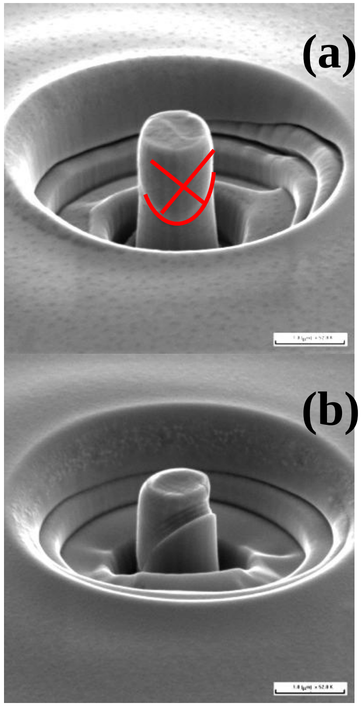
Conclusion

- The shear stress at the very first pop-in during nanoindentation of as-grown ZnO wafer occurs at about 4.9 GPa, which is about $\mu/10$, where μ (~40 GPa) is the shear modulus of ZnO.

- For the annealed sample, the resolved shear stress (~4.9 GPa) at the first pop-in is essentially the same. This is expected since the theoretical shear strength is an intrinsic property.

Microcompression





$$E = \left(\frac{P}{\Delta h}\right)\left[\frac{\ln\left(1+\frac{2\theta h_0}{d_0}\right)}{\pi d_0}\right]$$

Conclusion

- The corrected moduli of the as-grown and annealed micropillars are computed to be 123±17 and 120±15 GPa, respectively.

- The σ_{ys} and τ_p of annealed pillar is 2.7 GPa and 1 GPa, respectively.

- The σ_{ys} and τ_p of annealed pillar decrease to 1.7 GPa and 0.6 GPa, respectively.

Thank you for your attention!