3. Technical Review – Materials

Basics – Mechanics of Materials

- Stress: N/m^2, Pa or psi

  $\sigma = P/A_0$

  P: load on the sample

  A_0: original(zero-stress) cross sectional area

- Strain: unitless

  $\varepsilon = (l - l_0)/l_0 = \Delta l / l_0$

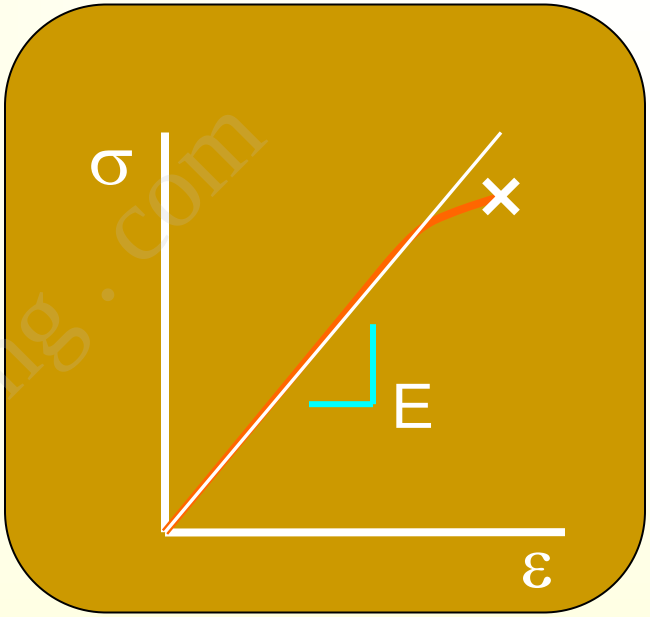
  l : sample length

  l_0: original(zero-stress) length

- Hooke's law

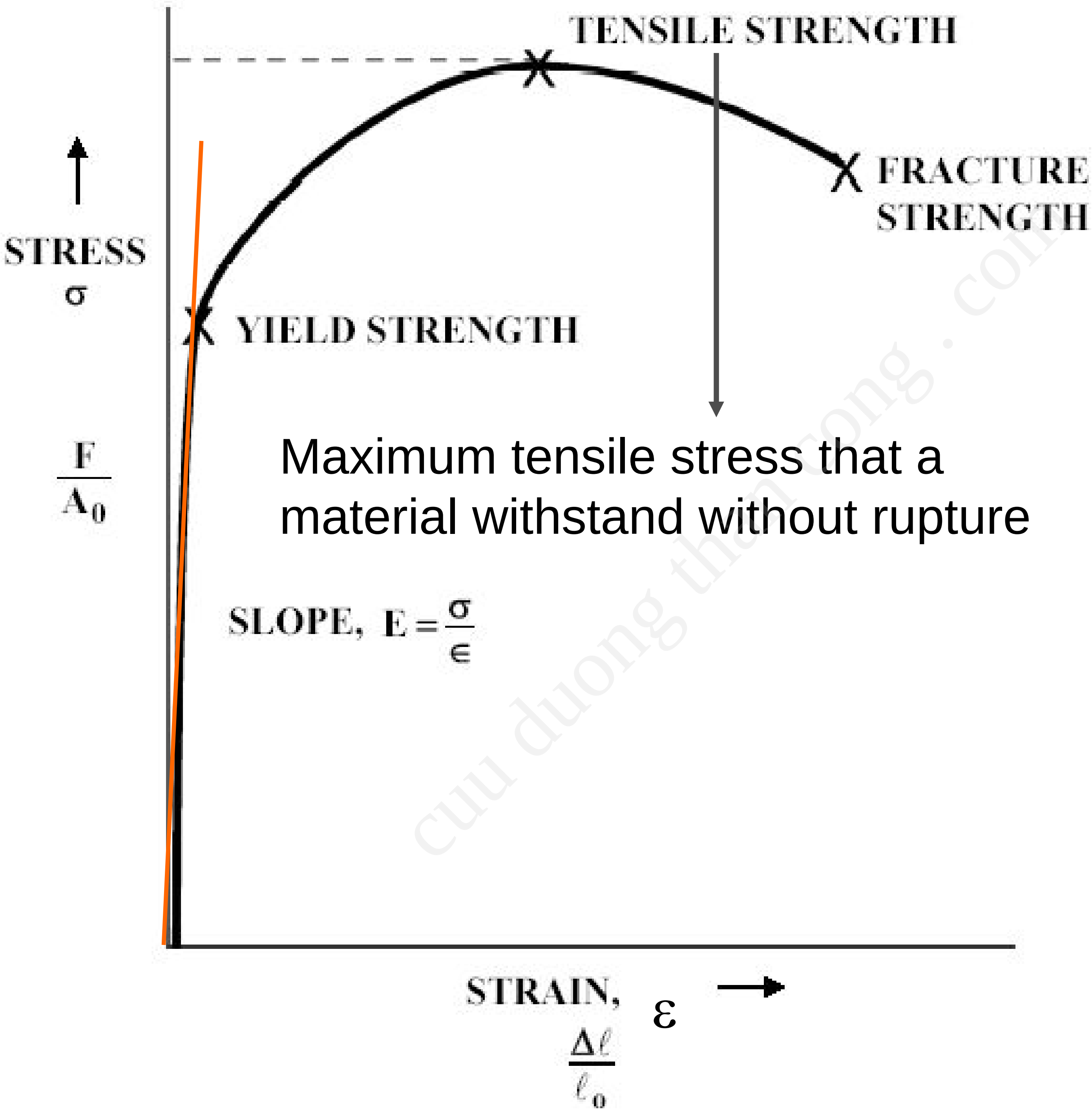
  $\sigma = E\varepsilon$

  E: Young's modulus or elastic coefficient



- Yield strength

  The stress at which a material exceeds its elastic limits and the material begins to deform permanently



Maximum tensile stress that a material withstand without rupture

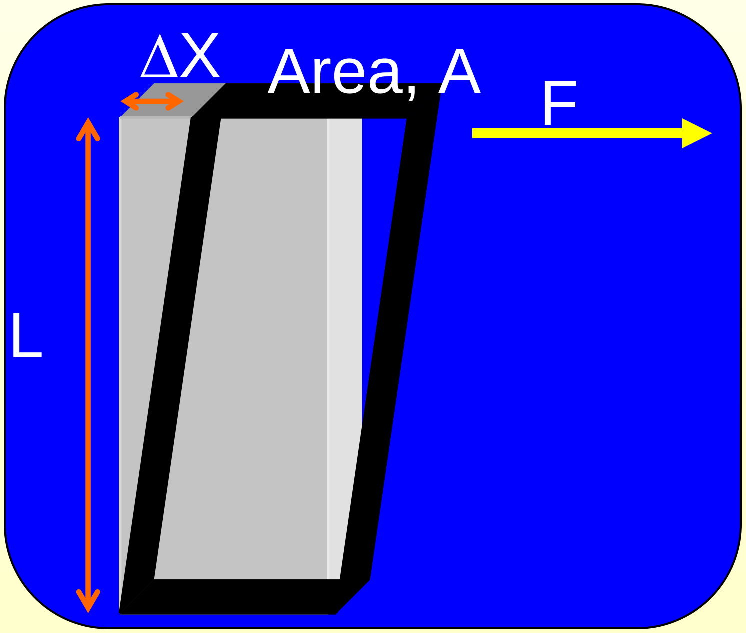
- Shear stress and strain

τ= F/A

Shear modulus: G

G = shear stress/shear displacement angle

= τ/γ = (F/A)/(ΔX/L)



- Poisson's ratio

Under axial load,

$\varepsilon(\text{axial}) = \Delta l / l_0$

$\varepsilon(\text{transverse}) = \Delta d / d_0$

Poisson's ratio;

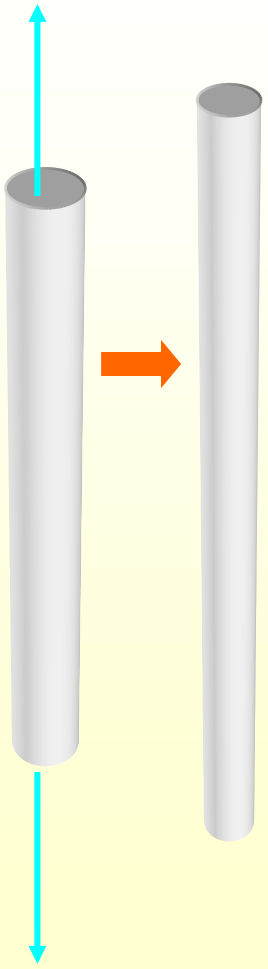
ν = transverse strain/longitudinal strain

$= -\varepsilon(\text{transverse}) / \varepsilon(\text{axial})$

Typical values are 0.2 to 0.5

- Relation of E and G

$E = 2G(1 + \nu)$



SCS(Single Crystal Silicon)

- Anisotropic : crystal
- Elastic : catastrophic failure
- Young's modulus = 190GPa < 200(SS)
- Hardness = 850 kg/mm^2 > 660(SS)
- Yield strength = 7x 10^9 N/m^2 > $2.1x10^9$(SS)
- Mightier than we think !

Material	Yield Strength (10^9 N/m²)	Knoop Hardness (kg/mm²)	Young's Modulus (GPa)	Density (g/cm³)	Thermal Conductivity (W/cm•K)	Thermal Expansion Coefficient (10^6/K)
*Diamond	53	7,000	1,035	3.5	20	1
*SiC	21	2,480	700	3.2	3.5	3.3
*TiC	20	2,470	497	4.9	3.3	6.4
*Al_2O_3	15.4	2,100	530	4	0.5	5.4
*Si_3N_4	14	3,486	385	3.1	0.19	0.8
*Iron	12.6	400	196	7.8	0.803	12
SiO_2 (fibers)	8.4	820	73	2.5	0.014	0.55
*Si	7	850	190	2.3	1.57	2.33
Steel (max strength)	4.2	1,500	210	7.9	0.97	12
W	4	485	410	19.3	1.78	4.5
Stainless Steel	2.1	660	200	7.9	0.329	17.3
Mo	2.1	275	343	10.3	1.38	5
Al	0.17	130	70	2.7	2.36	25

From Kovacs

- Limiting factors
  - Crystallographic defects and planes
  - Residual stress from high temperature process and film structure

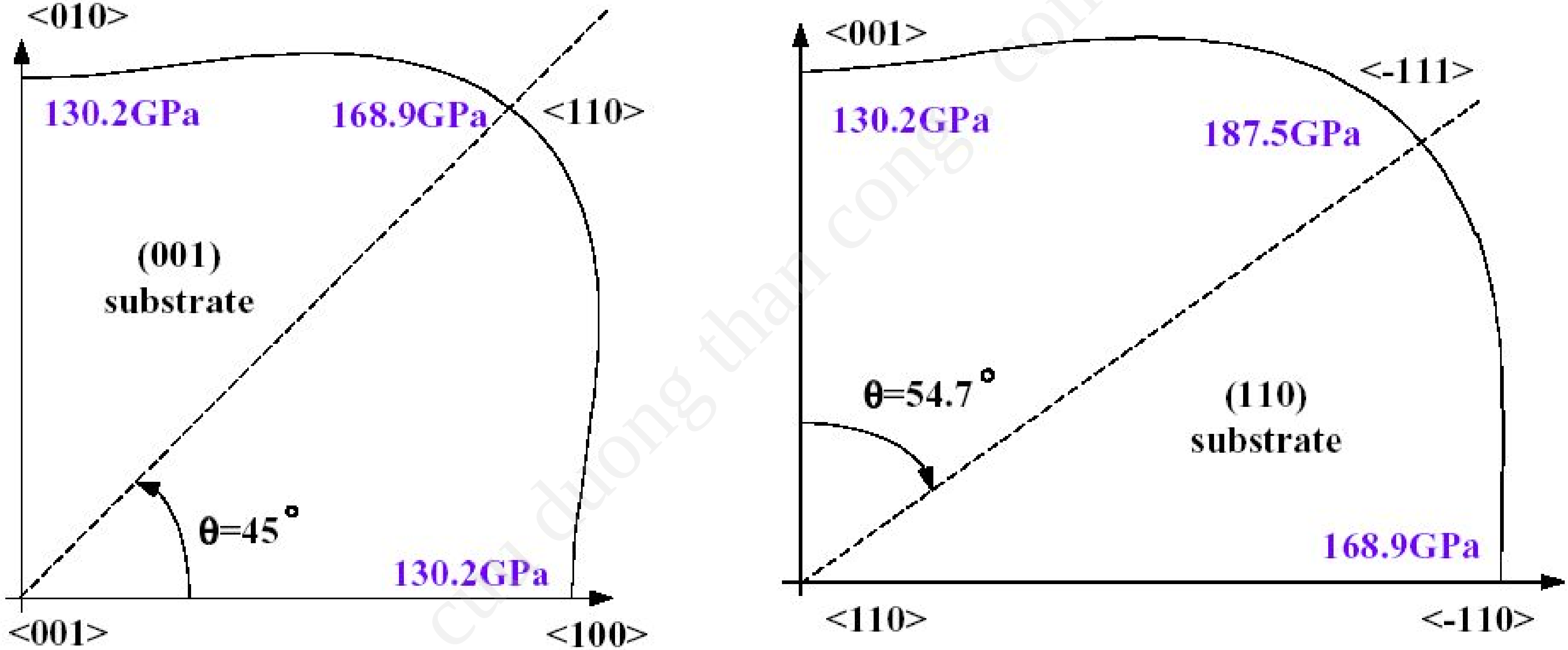
- How to overcome?
  - Stress consideration from design stage
  - Minimize defects during dicing, grinding and polishing
  - Tribological measure: coating and lubrication
  - Low temperature process

- Because of anisotropy of cubic system, elastic coefficient is 6x6 matrix in the form of,

$$C_{ij} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{pmatrix}$$

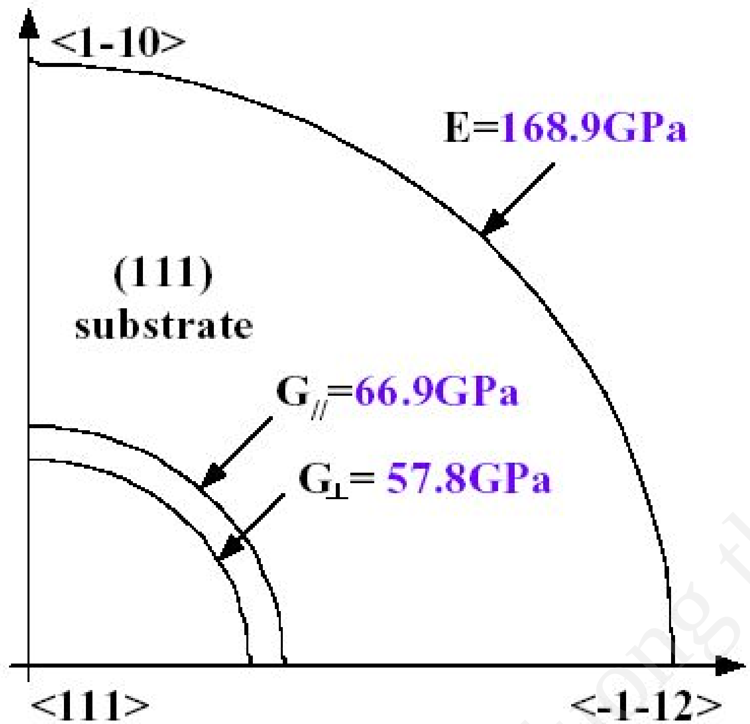
for [100] axis loading

Young's modulus vs crystallographic orientation in SCS



(a) Young's modulus on silicon (100)

(b) Young's modulus on silicon (110)



(g) Young's modulus and Shear modulus on silicon (111)

(111) planes can be considered as isotropic

From J. Kim, D. Cho and R. S. Muller, "Why is a (111) silicon better mechanical material for MEMS", Transducers '01, 11th Int'l Conf. Solid State Sensors and Actuators, Munich, Germany, June 10-14, 2001

Doping effect

- Tensile or compressive stress is induced on the doped area from local contraction or expansion of lattice, which becomes critical in thin membrane or beam structure.
- p-type Si with Boron
  - tensile residual stress
- n-type Si with Phosphorus
  - compressive residual stress
- p++ etch stop: heavily doped Si (with Boron >7 x10^{19}cm^{-3}) is frequently used for membrane or beam fabrication

Piezoresistivity

- Change of bulk resistivity by the mechanical stress applied to the material
- Stress → Strain → Volume change → Energy gap change → Number of charge carriers change → Resistivity change
- SCS has a high pzr with excellent mechanical properties, therefore is widely used for electromechanical transducers

- Principle

$R_0 = \rho_0 \, l/wt$

$\Delta R/R_0 = \Delta l/l - \Delta w/w - \Delta t/t + \Delta \rho/\rho_0$

Using Poission's ratio, ν

$\Delta w/w = \Delta t/t = -\nu \Delta l/l$

Gauge factor GF (strain sensitivity) is,

$$GF = \frac{\Delta R/R_0}{\varepsilon} = 1 + 2\nu + \frac{\Delta \rho/\rho_0}{\varepsilon}$$

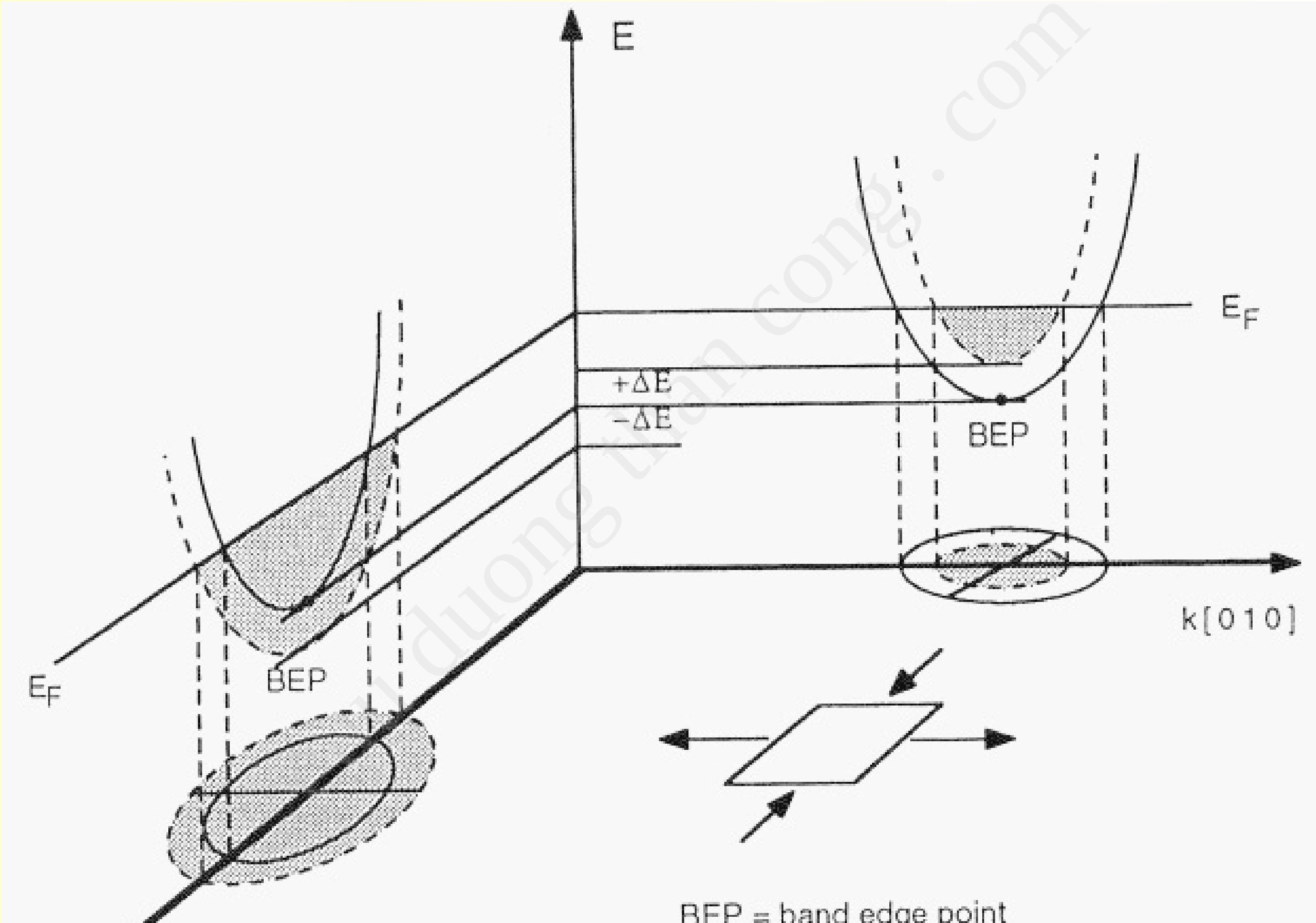
Dimensional change ($1 + 2\nu$)

Resistivity change ($\frac{\Delta \rho/\rho_0}{\varepsilon}$)

Advantages

- GF(SCS) = 80 to 200 compared to GF(metal) = 1 to 5
- High sensitivity and good linearity of pzr elements
- Robustness of Si
- Ease of integration with IC
- Resistors can be located where the stress is maximum (on the surface)
- Relatively simple calibration and compensation of pzr elements

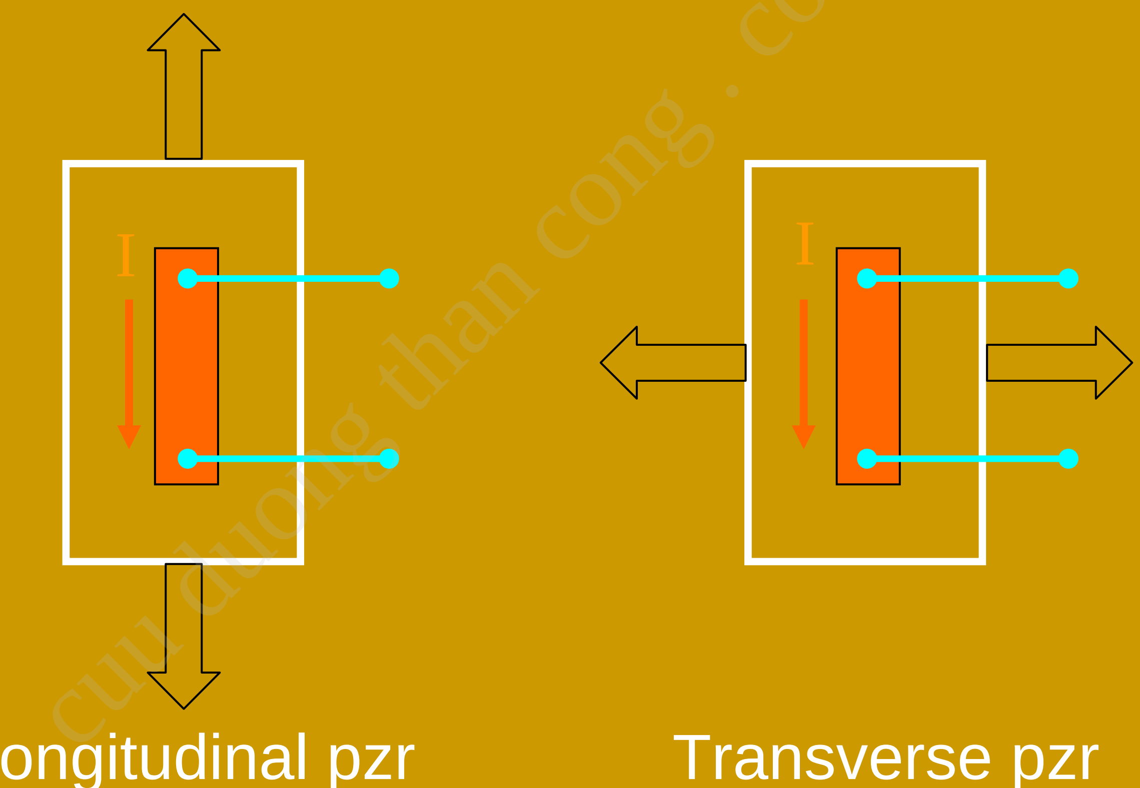
Origin of PZR: Many-valley energy theory



Mobility is lowest along <100>

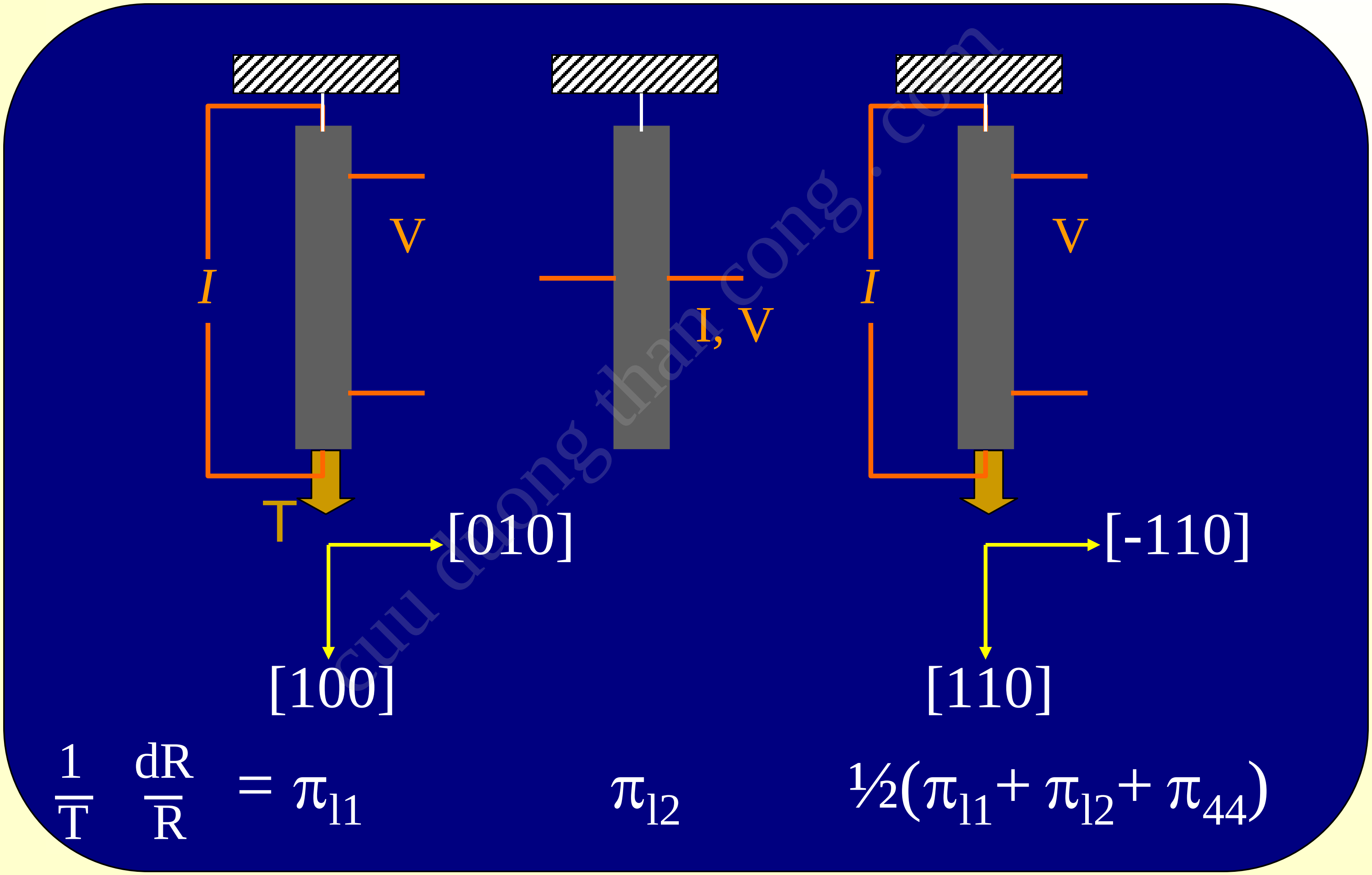
- Depending on the direction, an electron has different combination of k_1, k_2, and k_3 in SCS.
- Silicon has three pairs of valleys. Valleys are are identical except for orientation.
- Constant energy surface with unequal lengths (along principal axes) → different effective masses and mobilities → electrons make anisotropic contribution to conductivity
- Uncompressed : all valleys are equally populated → isotropic conductivity
- Under anisotropic stress: relative energies change → electrons transfer from one valley to another → populations change, mobilities change → anisotropic conduction

Longitudinal and transverse piezoresitance coefficient

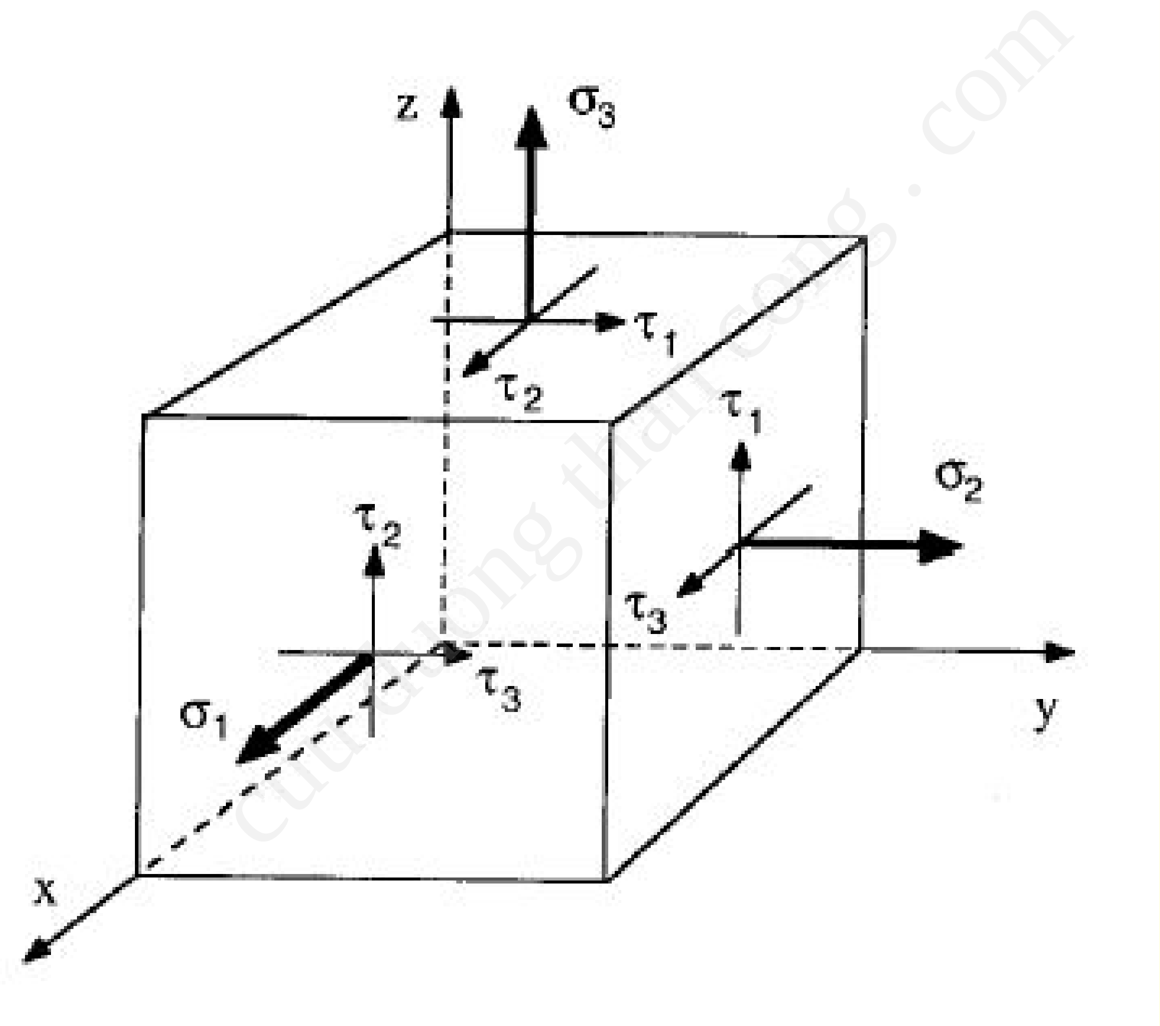


$$\Delta R/R = \pi_l\, \sigma_l + \pi_t\, \sigma_t$$

❑ Measurement



- For SCS (cubic system)



❑ General expression of pzr for SCS

$$\frac{1}{\rho}\begin{bmatrix}\Delta\rho_1\\ \Delta\rho_2\\ \Delta\rho_3\\ \Delta\rho_4\\ \Delta\rho_5\\ \Delta\rho_6\end{bmatrix}=\begin{bmatrix}\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & \pi_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & \pi_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & \pi_{44}\end{bmatrix}\cdot\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_1\\ \tau_2\\ \tau_3\end{bmatrix}$$

❑ PZR coefficients for cubic crystal

Longitudinal Direction	π_l	Transverse Direction	π_t
(1 0 0)	π_{11}	(0 1 0)	π_{12}
(0 0 1)	π_{11}	(1 1 0)	π_{12}
(1 1 1)	$\frac{1}{3}(\pi_{11}+2\pi_{12}+2\pi_{44})$	(1 $\bar{1}$ 0)	$\frac{1}{3}(\pi_{11}+2\pi_{12}-\pi_{44})$
(1 1 $\bar{0}$)	$\frac{1}{2}(\pi_{11}+\pi_{12}+\pi_{44})$	(1 1 1)	$\frac{1}{3}(\pi_{11}+2\pi_{12}-\pi_{44})$
(1 1 $\bar{0}$)	$\frac{1}{2}(\pi_{11}+\pi_{12}+\pi_{44})$	(0 0 1)	π_{12}
(1 1 0)	$\frac{1}{2}(\pi_{11}+\pi_{12}+\pi_{44})$	(1 $\bar{1}$ 0)	$\frac{1}{2}(\pi_{11}+\pi_{12}-\pi_{44})$

❑ PZR coefficients for SCS at RT (unit: 10^{-11} Pa^{-1})

	ρ (Ohm-cm)	π_{11}	π_{12}	π_{44}
p-Si	7.8	6.6	-1.1	138.1
n-Si	11.7	-102.2	53.4	-13.6

- Resistance changes as a function of stress

$$\Delta R/R = \pi_l \sigma_l + \pi_t \sigma_t$$

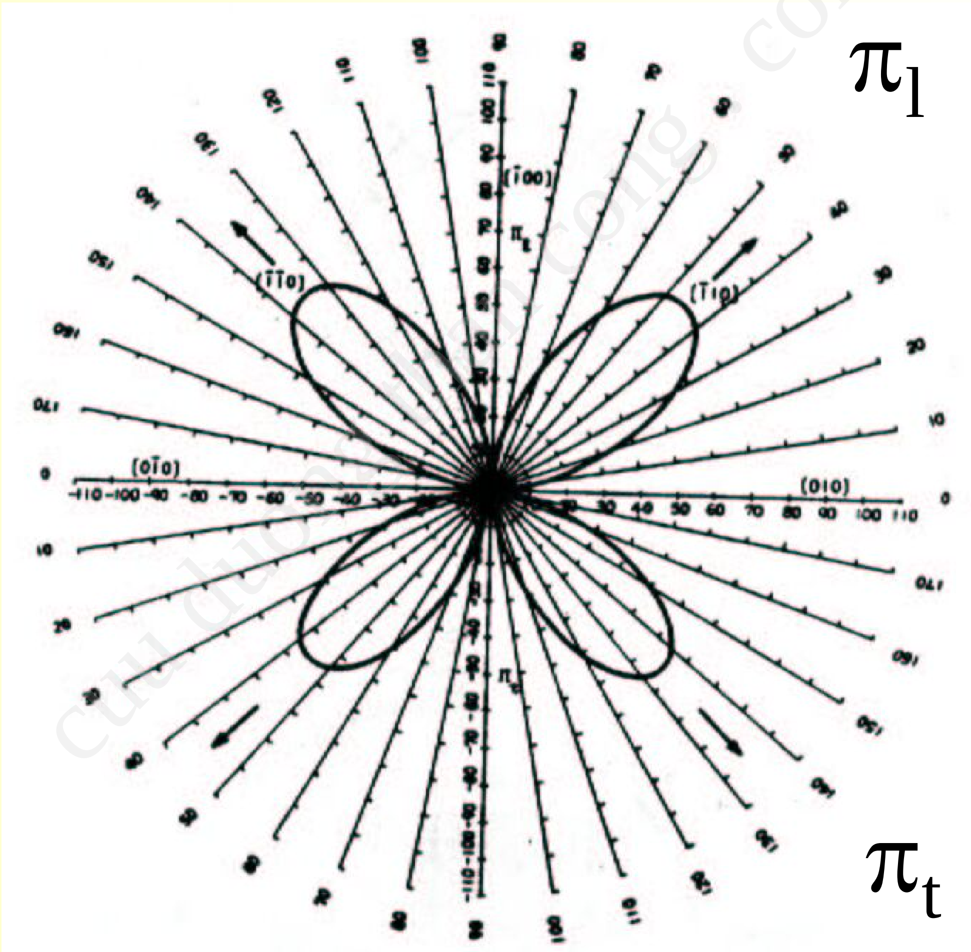
<110>, p-Si

$$\Delta R/R = (\pi_{44} /2) * (\sigma_l - \sigma_t)$$

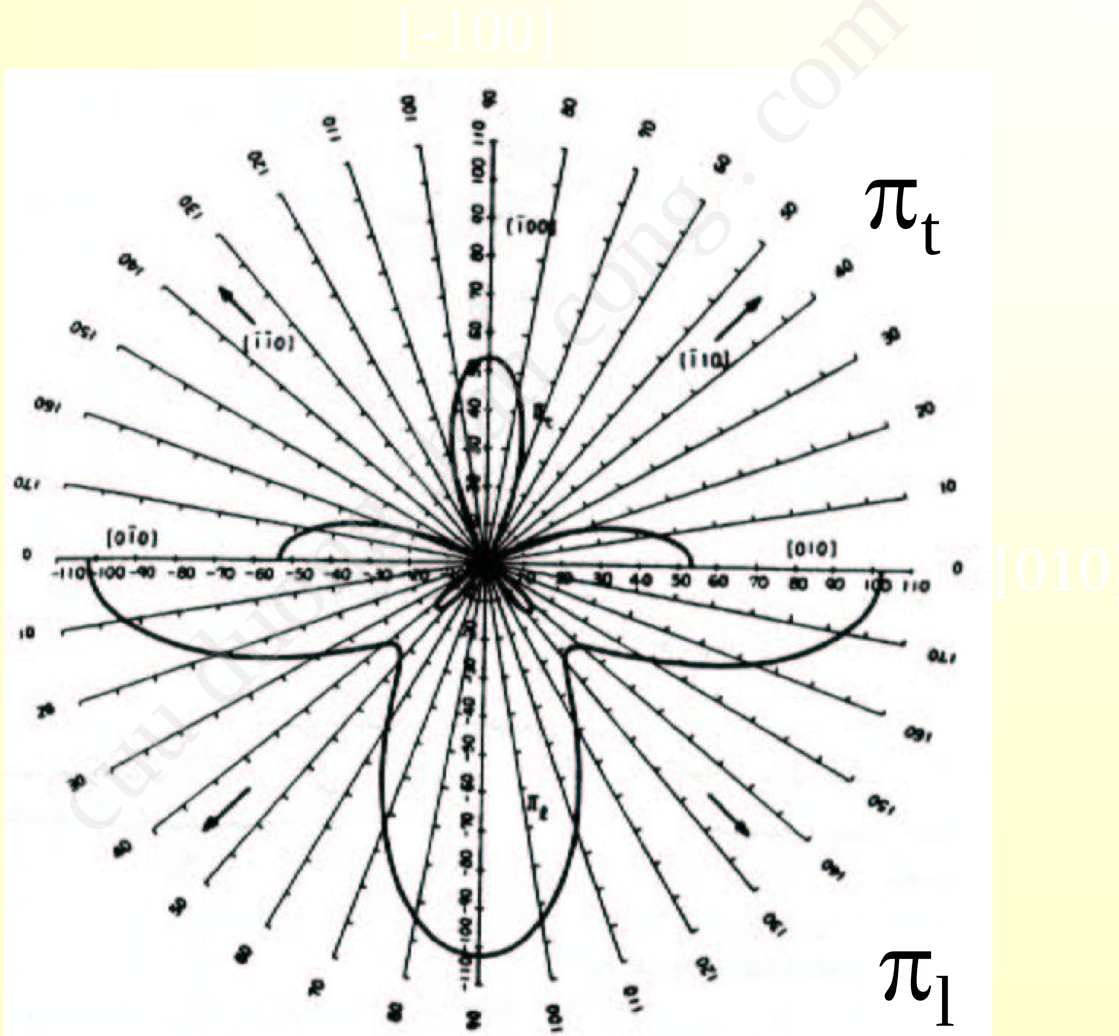
<110>, n-Si

$$\Delta R/R = (\pi_{11} + \pi_{12})/2 * (\sigma_l + \sigma_t)$$

❑ Piezoresistance coefficient vs. orientation: (001) p-Si

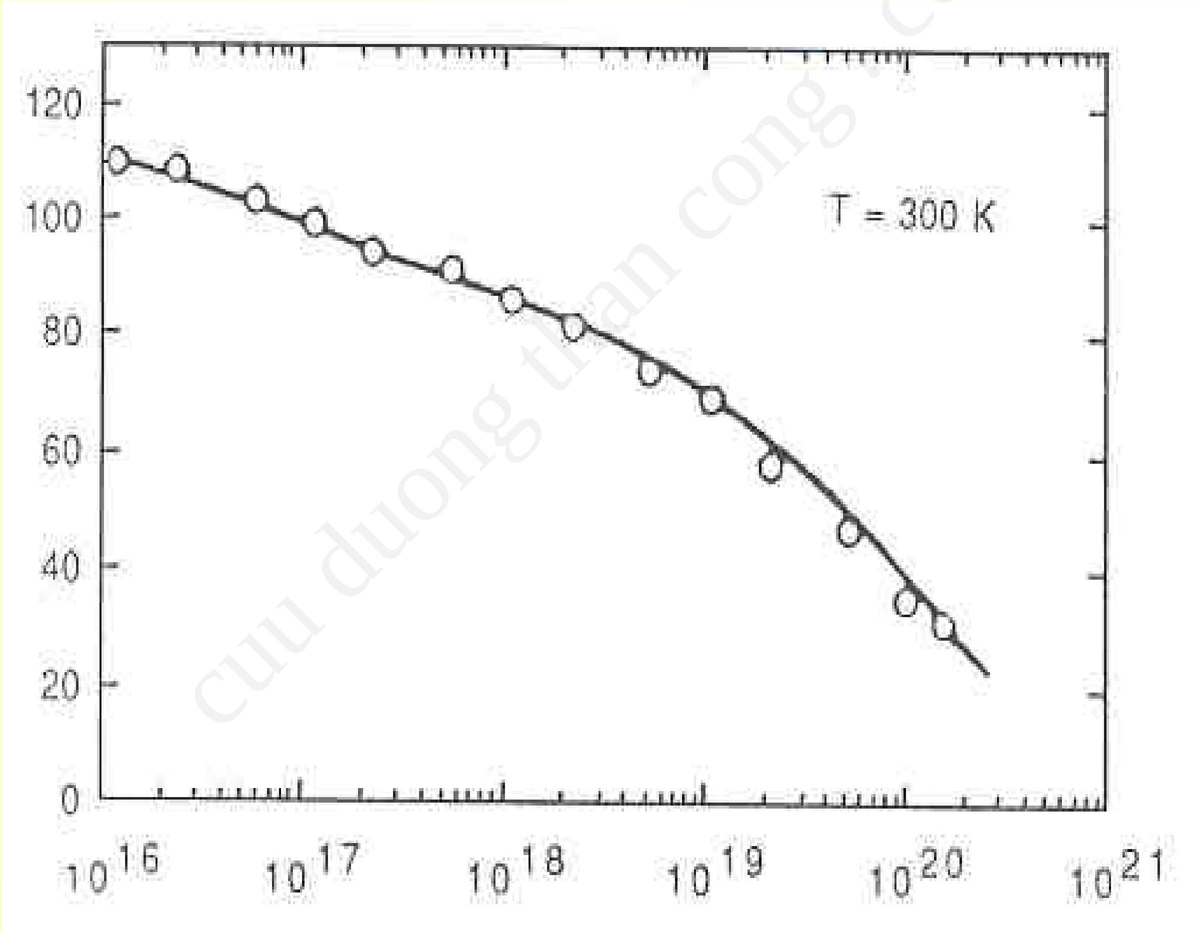


❑ Piezoresistance coefficient vs. orientation: (001) n-Si



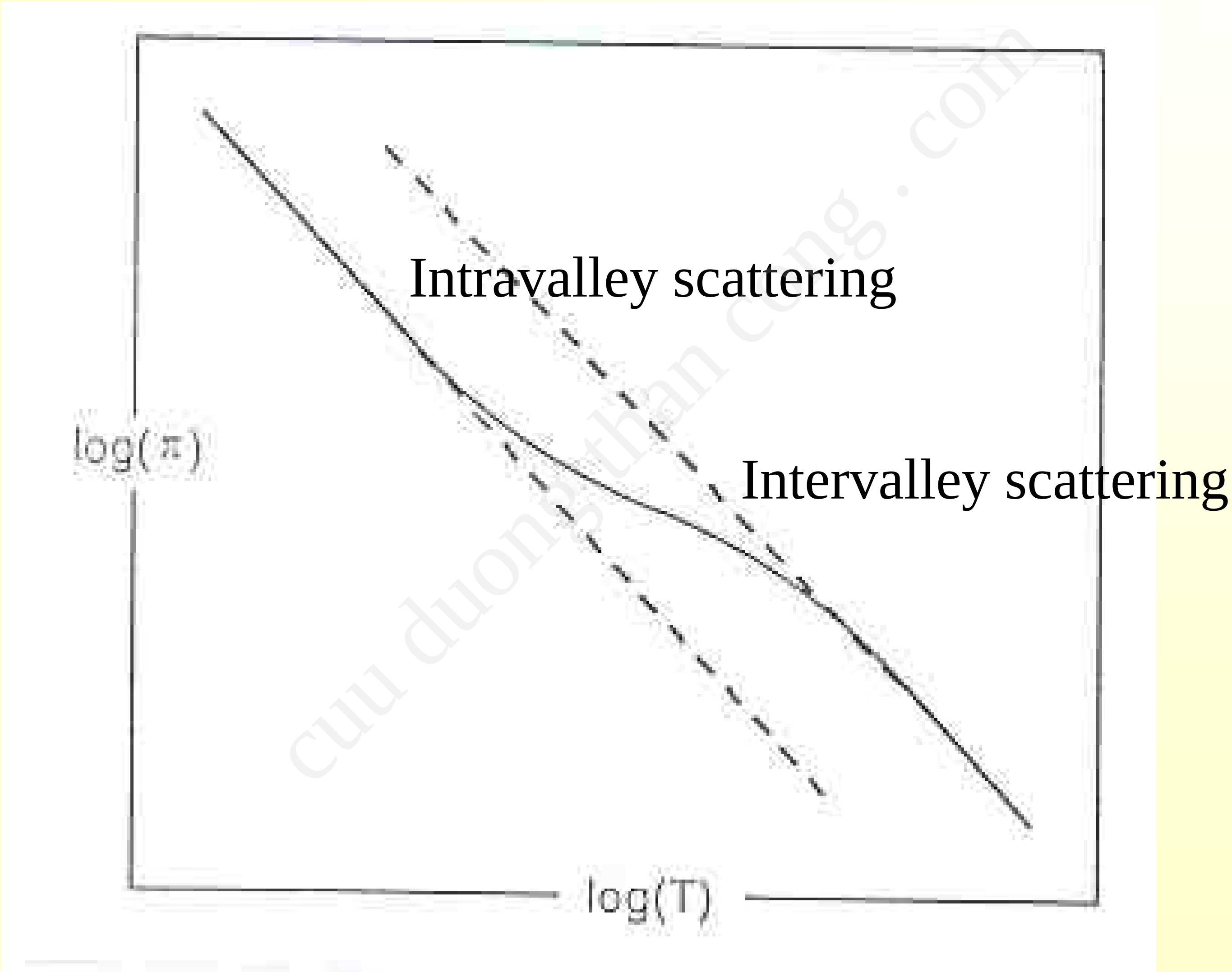
❑ π_{11} vs. impurity concentration in n-Si

$\pi_{11}(10^{-12}.cm^2/dyn)$



N (cm^{-3})

- Piezoresitance coefficient vs. temperature



Materials for Small Devices

- Substrates
  - Semiconductor: Si, Ge, GaAs
  - Insulator: glass, quartz and polymers
  - Others: various functional materials
- Additive materials
  - Structural: polysilicon
  - Electrical: conductors and insulators
  - Functional: active materials
- Packaging materials

Materials	Approximate electrical resistivity ρ, Ω-cm	Classification
Silver (Ag)	10^{-6}	Conductors
Copper (Cu)	$10^{-5.8}$	
Aluminum (Al)	$10^{-5.5}$	
Platinum (Pt)	10^{-5}	
Germanium (GE)	10^{-3}–$10^{1.5}$	Semiconductors
Silicon (Si)	10^{-3}–$10^{4.5}$	
Gallium arsenide (GaAs)	10^{-3}–10^{8}	
Gallium phosphide (GaP)	10^{-2}–$10^{6.5}$	
Oxide	10^{9}	Insulators
Glass	$10^{10.5}$	
Nickel (pure)	10^{13}	
Diamond	10^{14}	
Quartz (fused)	10^{18}	

Table 7.3 I Mechanical and thermophysical properties of MEMS materials*

Material	σ_y, 10^9 N/m²	E, 10^{11} N/m²	ρ, g/cm³	c, J/g-°C	k, W/cm-°C	α, 10^{-6}/°C	T_M, °C
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si_3N_4	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO_2	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067.0.12	7.10	1710

*Principal source for semiconductor material properties: *Fundamentals of Microfabrication*, Marc Madou, CRC Press, 1997

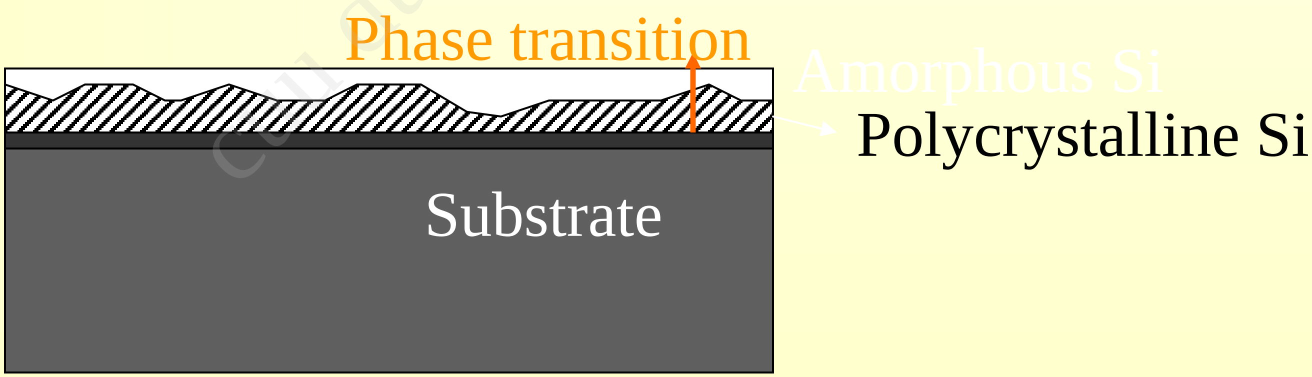
Legend: σ_y = yield strength, E = Young's modulus, ρ = mass density, c = specific heat, k = thermal conductivity, α = coefficient of thermal expansion, T_M = melting point.

Polysilicon

- Poly crystalline silicon
- Basic building block for surface micromachining
- Good mechanical properties
- Can be used for resistors, conductors and ohmic contacts
- Can form piezoresistors
- Easy to fabricate but difficult to control residual stress
- Properties are highly dependent on deposition and thermal history condition

Material	Coefficient of Thermal Expansion $10^{-6}/K$	Young's Modulus GPa	Thermal Conductivity W/m·K	Density g/cm^3
Si	2.33 [2] 2.6 [4]	190 [2] 162 [4]	149 [2] 170 [4]	2.3 [2] 2.42 [4]
SiO_2	0.4 [4]	92 (sputtered) [1] 67 (dry) [1] 57 (wet) [1] 70 (bulk) [1]	1.4 [4]	2.66 [4] 2.3 (plasma) [6]
Si_3N_4	2.8 [4]	146 (CVD) [1] 130 (sputtered) [1]	18.5 [4]	3.44 [4] 2.9 to 3.1 (LPCVD) [6] 2.4 to 2.8 (PECVD) [6]
Poly-Si	2.33 [4]	150 [5]	20 to 30 [3]	2.33 [4]
Polyimide (PIQ L200, Hitachi)	2.0 [7]	8.63 [7]	-	-
Polyimide (PIQ 3200, Hitachi)	54 [7]	2.95 [7]	-	-
Aluminum	23.0 [4]	69 [4]	236 [2] 234 [4]	2.7 [2] 2.692 [4]
Gold	14.3 [4]	80 [4]	318 [4]	19.4 [4]
Platinum	8.9 [4]	147 [4]	73 [4]	21.4 [4]
Nickel	12.8 [4]	210 [4]	90.9 [4]	9.04 [4]

- Deposition of polysilicon
  - Source gas: Silane
  - LPCVD or PECVD
  - SiH_4(diluted in N_2) $\rightarrow$ Si + H_2 at 600-650^{o}C
  - Transition(amorphous to crystalline) at 560-600 ^{o}C for LPCVD
  - Nucleation and crystallization
  - Decreasing deposition rate, increasing thickness, increasing temperature $\rightarrow$ crystallization$\uparrow$ polySi phase$\uparrow$



Film stress

- Residual stress and stress gradient are dependent on deposition condition
- Film stress (Stoney's equation)

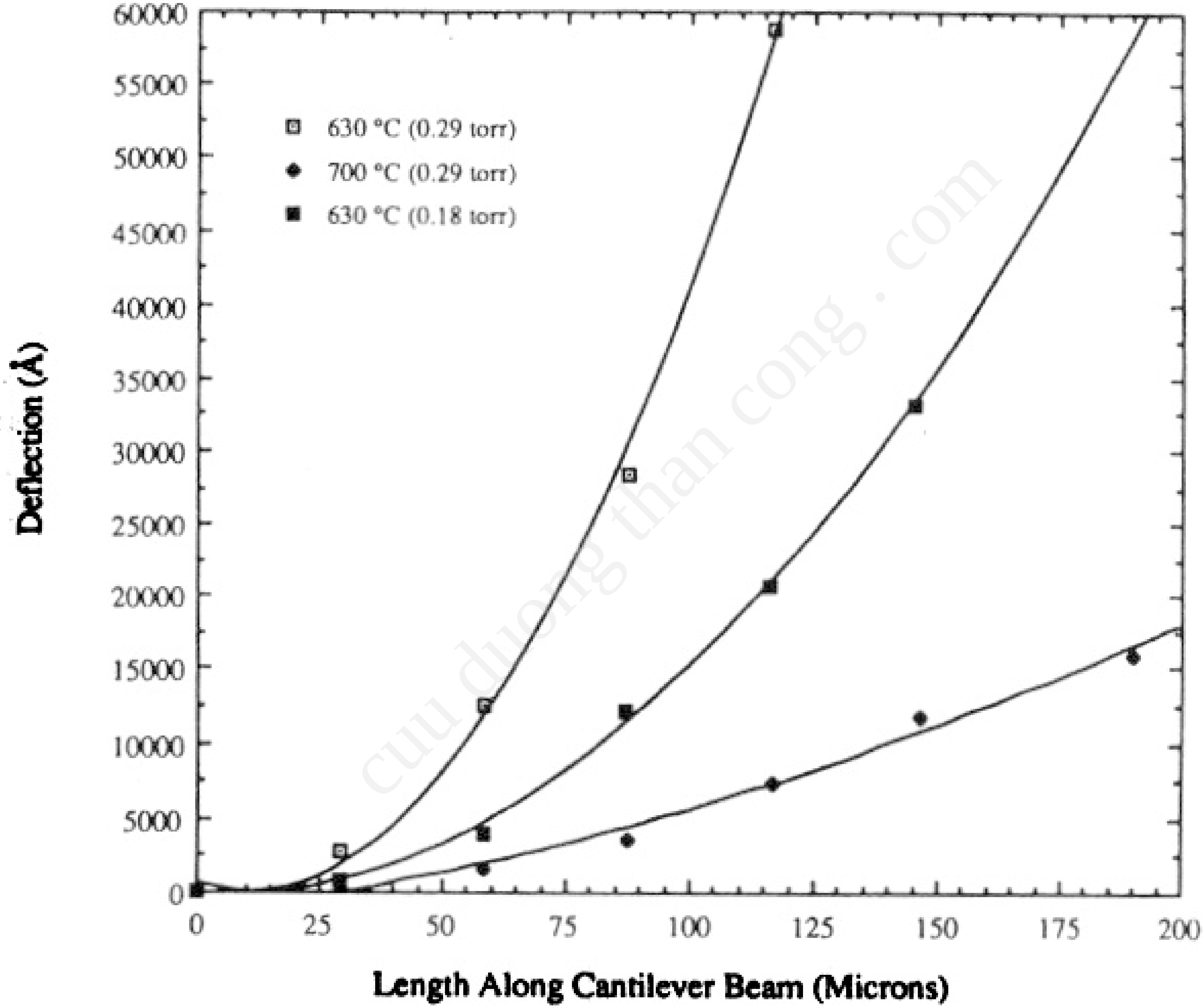
$$\sigma_f = \frac{E_s\, t_s^2}{6(1-\nu)\, t_f\, R_c}$$

R_c: radius of curvature, E_s :Young's modulus

t_s : substrate thickness, t_f: film thickness

ν : Poisson's ratio

- Compressive up to 700 Mpa (as deposited)
- Stress gradient over thickness


60000
55000
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Deflection (Å)
630 °C (0.29 torr)
700 °C (0.29 torr)
630 °C (0.18 torr)
0
25
50
75
100
125
150
175
200
Length Along Cantilever Beam (Microns)

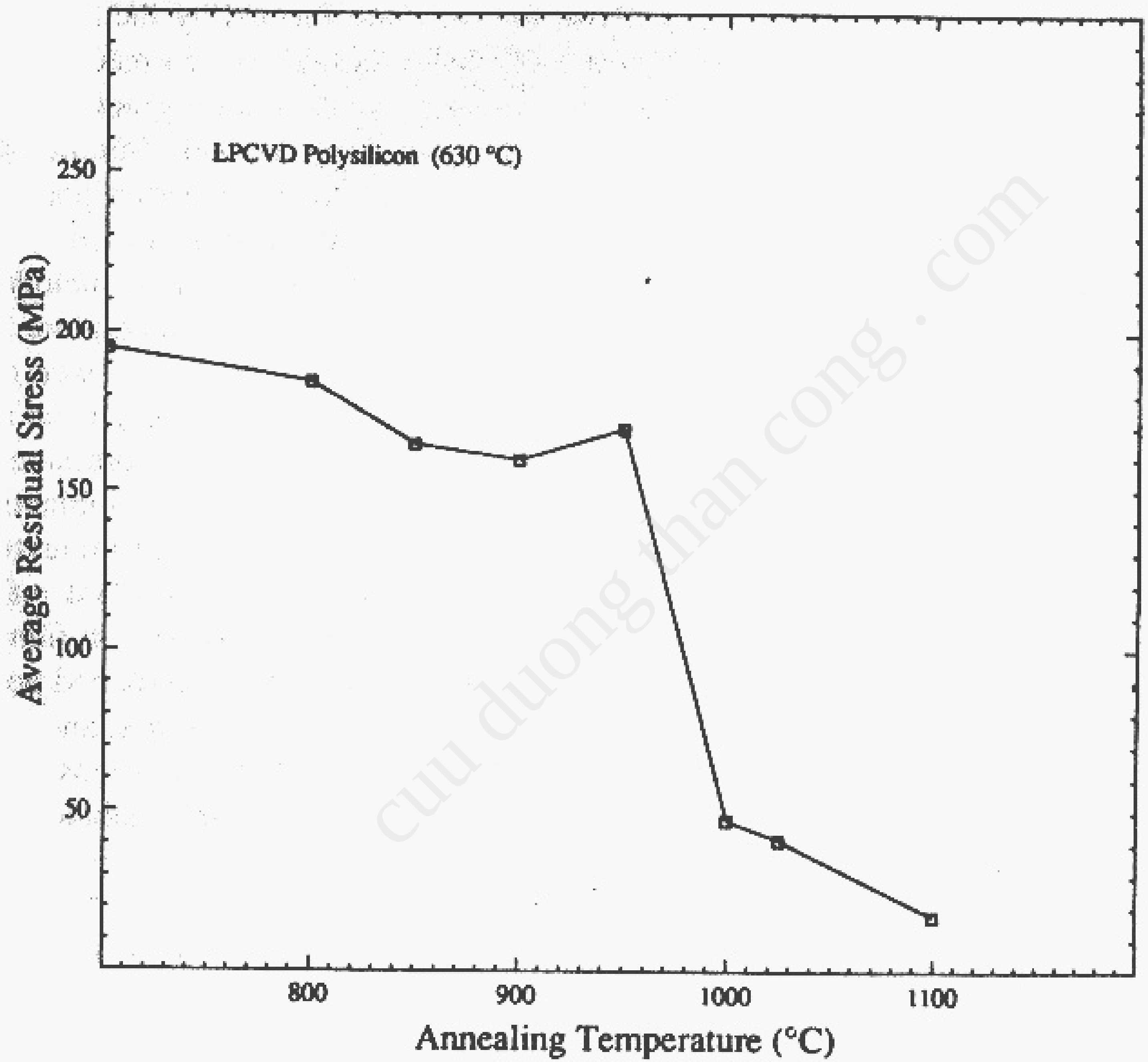
- Increasing deposition temperature reduces residual stress and stress gradient

Study of microstructure shows:

- <110> crystalline film shows highest stress
- Randomly oriented film shows lowest stress
- Reduced pressure (10^{-2}- 10^{-3} torr) and relatively high temperature(>700^{o}C) yield low stress by generating randomly oriented films

Annealing

- Annealing(above 900°C) reduces residual stress present in the as-deposited film
- Crystallization and grain growth
- Residual stress strongly depends on annealing condition


LPCVD Polysilicon (630 °C)
Average Residual Stress (MPa)
250
200
150
100
50
800
900
1000
1100
Annealing Temperature (°C)

- Doping

- In-situ doping (during deposition)

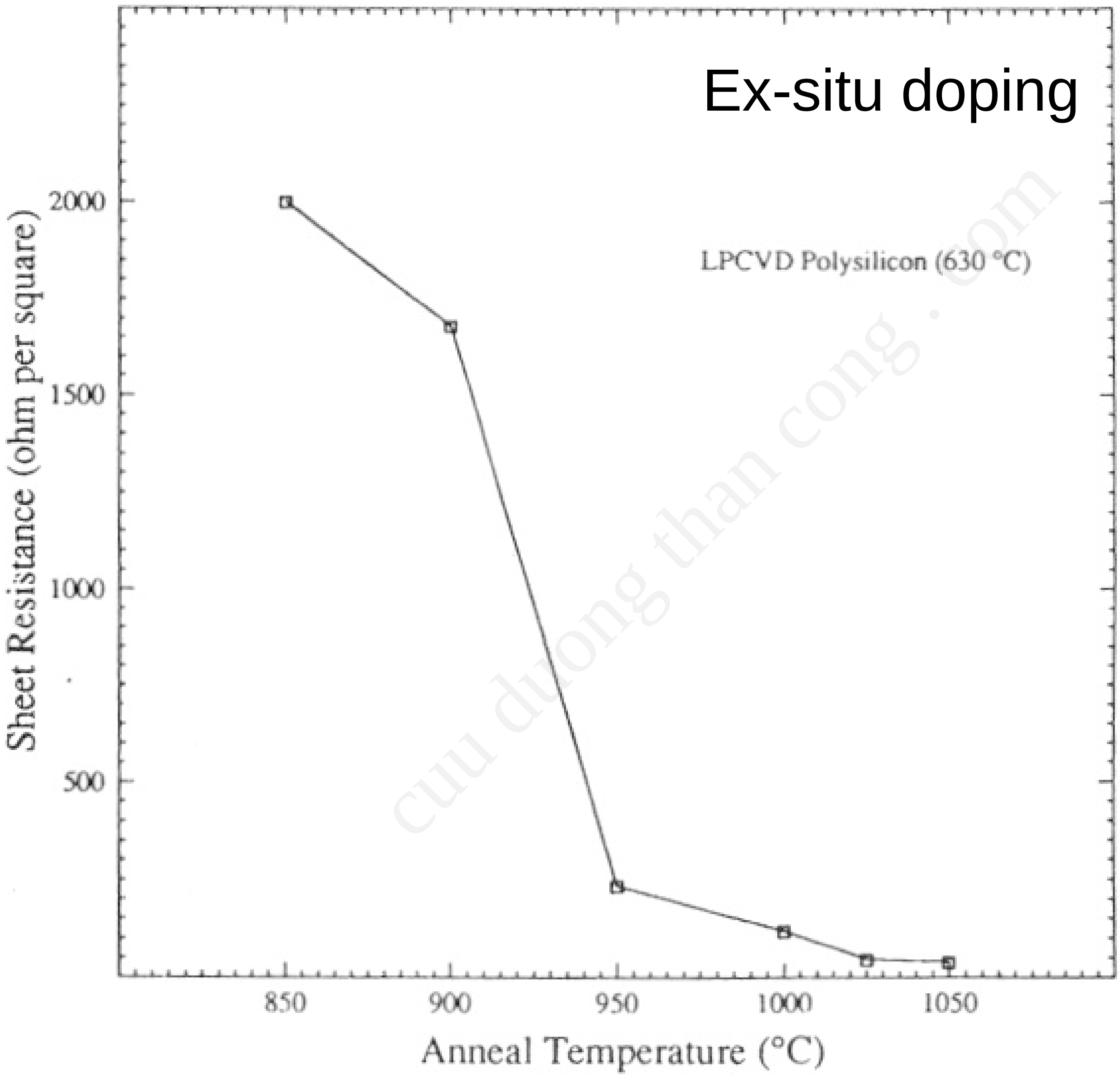
  Use Arsane(AsH_3), Phospine(PH_3) or Diborane(B_2H_3)

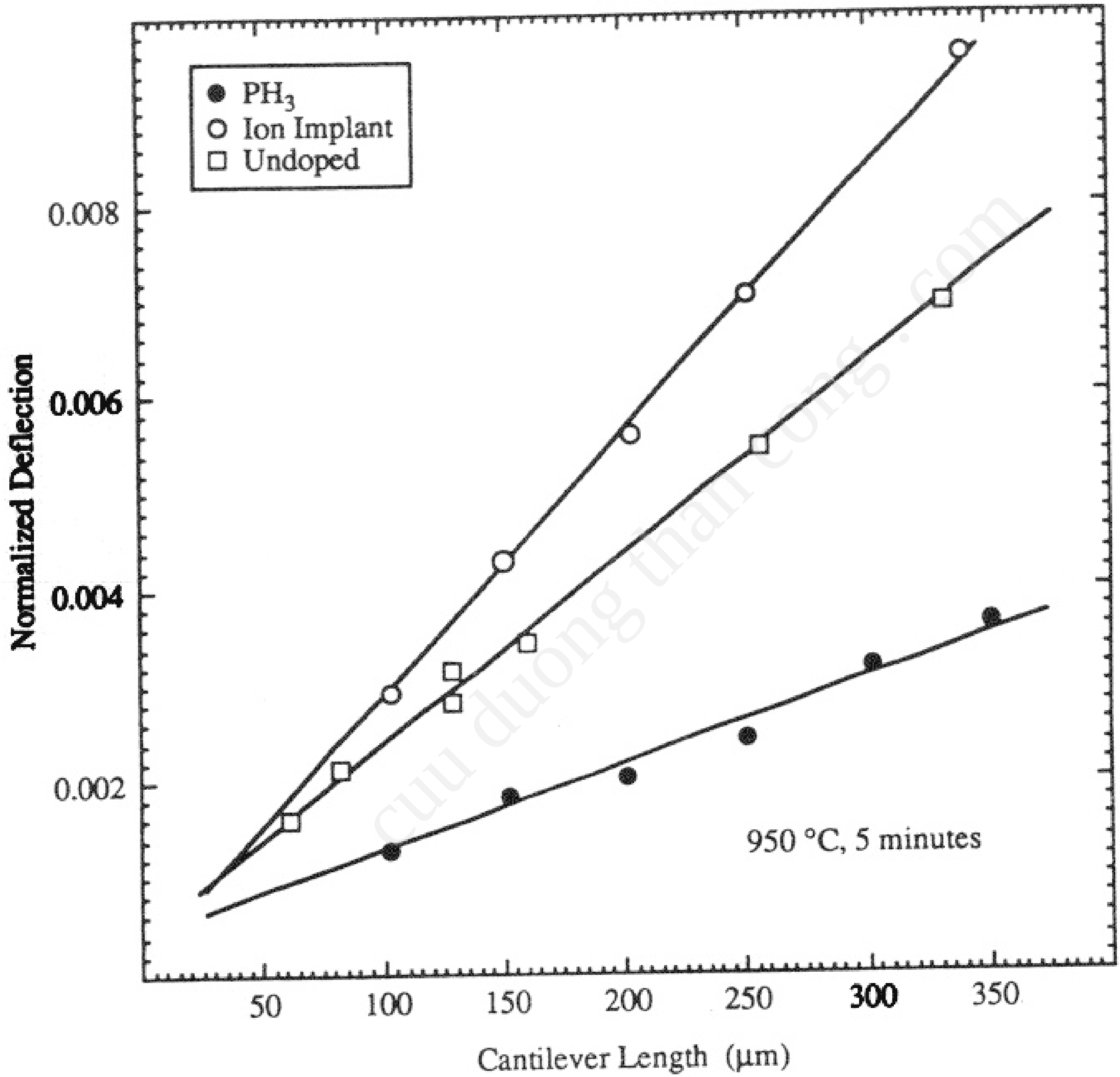
  : preferential adsorption of phospine to substrate suppress polySi growth rate

- Ex-situ doping

  Use phosphorus doped oxide layer (PSG, for sacrificial layer) – During thermal process, doped layer serves as a diffusion source

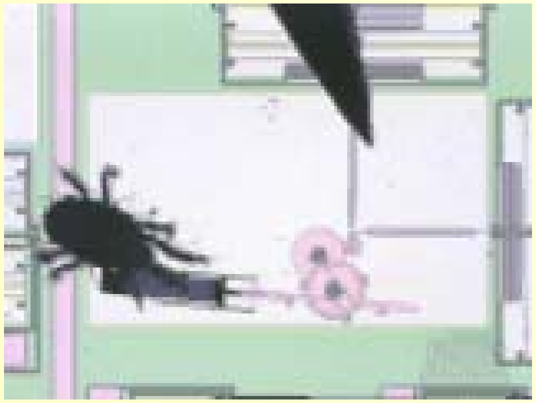
Ex-situ doping

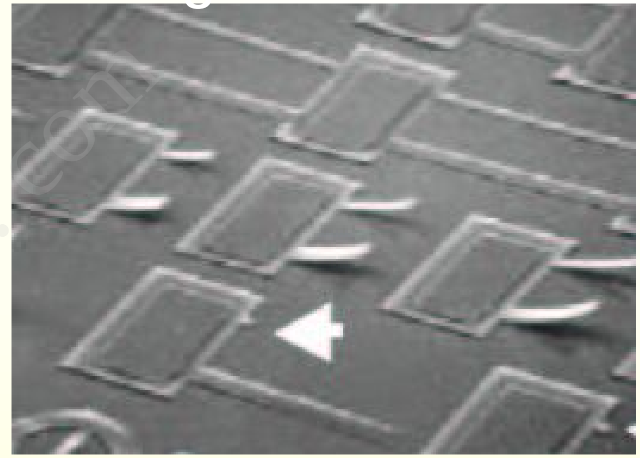


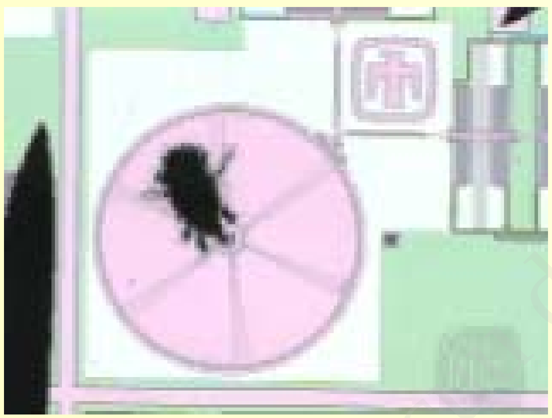


PH3
Ion Implant
Undoped
0.008
0.006
0.004
0.002
Normalized Deflection
950 °C, 5 minutes
50
100
150
200
250
300
350
Cantilever Length (µm)

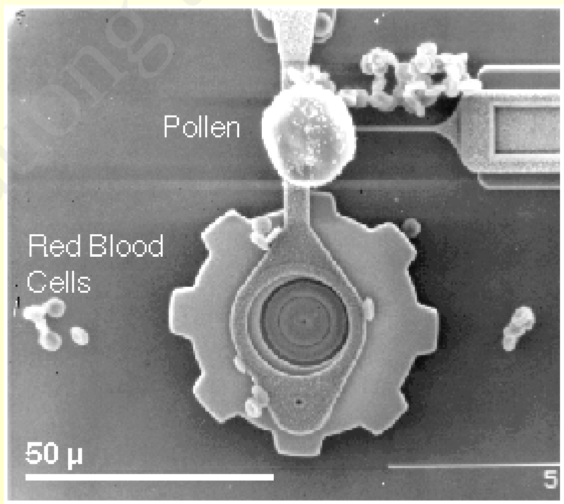
Deflection showing







cinstrum.unam.mx/revista/pdfv5n2/measuring.PDF



From Sandia National Lab

http://www.sandia.gov/mstc/technologies/micromachines/movies.html

Silicon nitride

- Use amorphous form for transducers
- Electrical Insulator (resistivity > 10^{15} ohm-cm for Si_3N_4)
- Etch mask: withstand HF and KOH
- Thermal insulator for high temperature
- Diffusion barrier to sodium
- High mechanical strength
- Can be deposited by sputter or CVD
- $3SiH_2Cl_2 + 4NH_3 \rightarrow Si_3N_4(s) + 6HCl + 6H_2$
- Large tensile stress (1-2GPa)
- Oxynitride ($Si_xO_yN_z$) reduces stress but has weak chemical resistance

Deposition Type	LPCVD	PECVD
Typical Temp.	700 to 800°C	< 250 to 350°C
Composition	$Si_3N_4(H)$	SiN_xH_y
Si/N Ratio	0.75	0.8 to 1.2
% H	4 to 8	20 to 25
Refractive Index	2.01	1.8 to 2.5
Density (g/cm^3)	2.9 to 3.1	2.4 to 2.8
Resistivity (Ω•cm)	10^{16}	10^6 to 10^{15}
Dielectric Strength (10^6 V/cm or 10^2 V/μm)	10	5
Energy gap (eV)	5	4 to 5
Stress (MPa)	1,000 tens (can be ≈ zero for Si rich films)	200 comp to 500 tens

Table of LPCVD and PECVD silicon nitride properties. After Adams (1983).

Silicon oxide

- Electrical insulator (resistivity > 10^{12} ohm-cm)
- Thermal insulator (conductivity <1.4×10^{-2} W/cm^{o}C)
- Can be deposited by sputter, CVD or spin-cast
- Can be thermally grown over Si conformally
- Can be formed to glass: PSG or BSG
- Compressive (~1GPa) for most cases
- Used for masking and sacrificial layer

- Strong adherence
- High selectivity over Si in buffered HF
- Excellent diffusion barrier

- Dry and wet oxidation

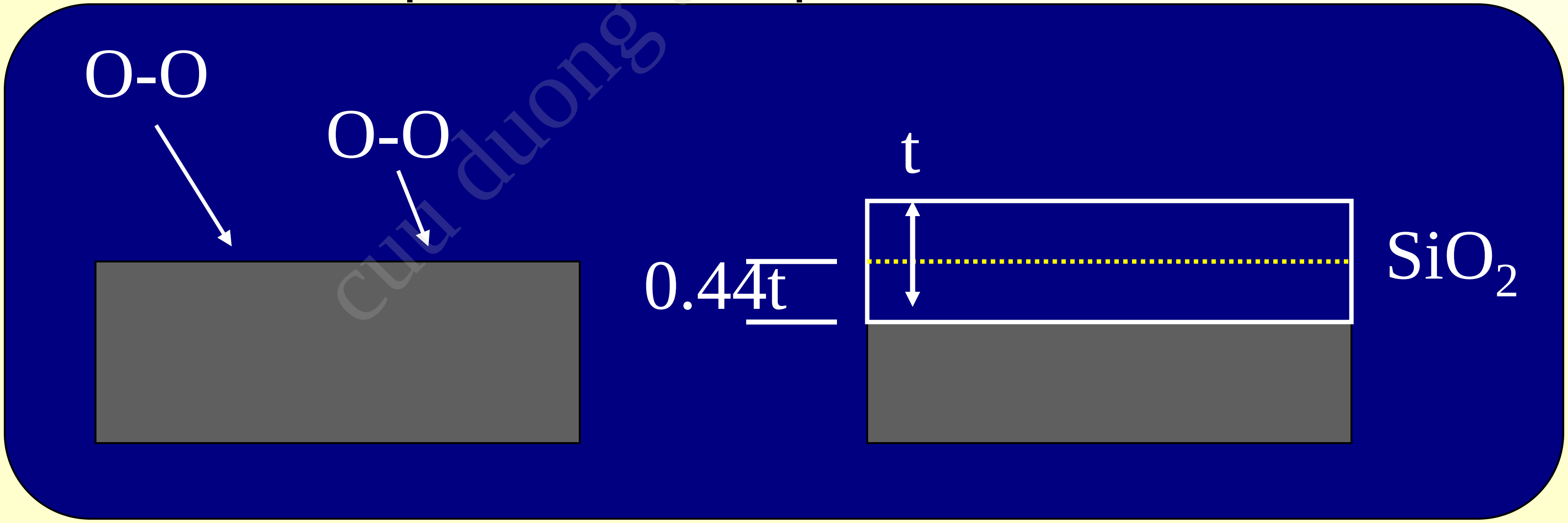
  $Si + O_2 \rightarrow SiO_2$

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

Molecular density of Si = 5×10^{22} atoms/cm^3

Molecular density of SiO_2 = 2.2×10^{22} molecules/cm^3

Oxide film expands $\rightarrow$ compressive stress



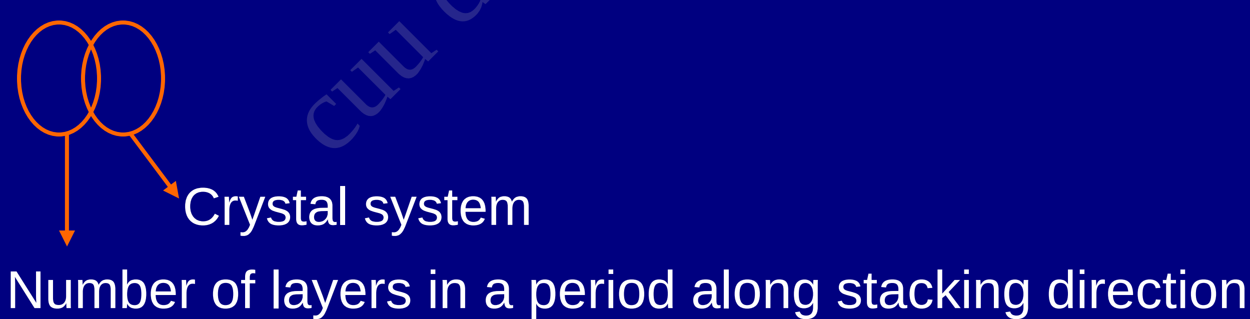
Deposition Type	PECVD	$SiH_4 + O_2$	TEOS	$SiCl_2H_2 + N_2O$	Native Oxide *(thermal)*
Typical Temp.	200°C	450°C	700°C	900°C	1,100°C
Composition	$SiO_{1.9}(H)$	$SiO_2(H)$	SiO_2	$SiO_2(Cl)$	SiO_2
Step Coverage	Varies (Adams says *nonconformal*)	Nonconformal	Conformal	Conformal	Conformal
Thermal Stability	Loses H	Densifies	Stable	Loses Cl	Excellent
Density (g/cm^3)	2.3	2.1	2.2	2.2	2.2
Refractive Index	1.47	1.44	1.46	1.46	1.46
Stress MPa	*300 comp to* 300 tens	300 tens	100 comp	300 comp	300 comp
Dielectric Strength (10^6 V/cm or 10^2V/μm)	3 to 6	8	10	10	10
Etch Rate (nm/min) *(100:1* H_2O:HF)	40	6	3	3	≈ 3

Silicon carbide

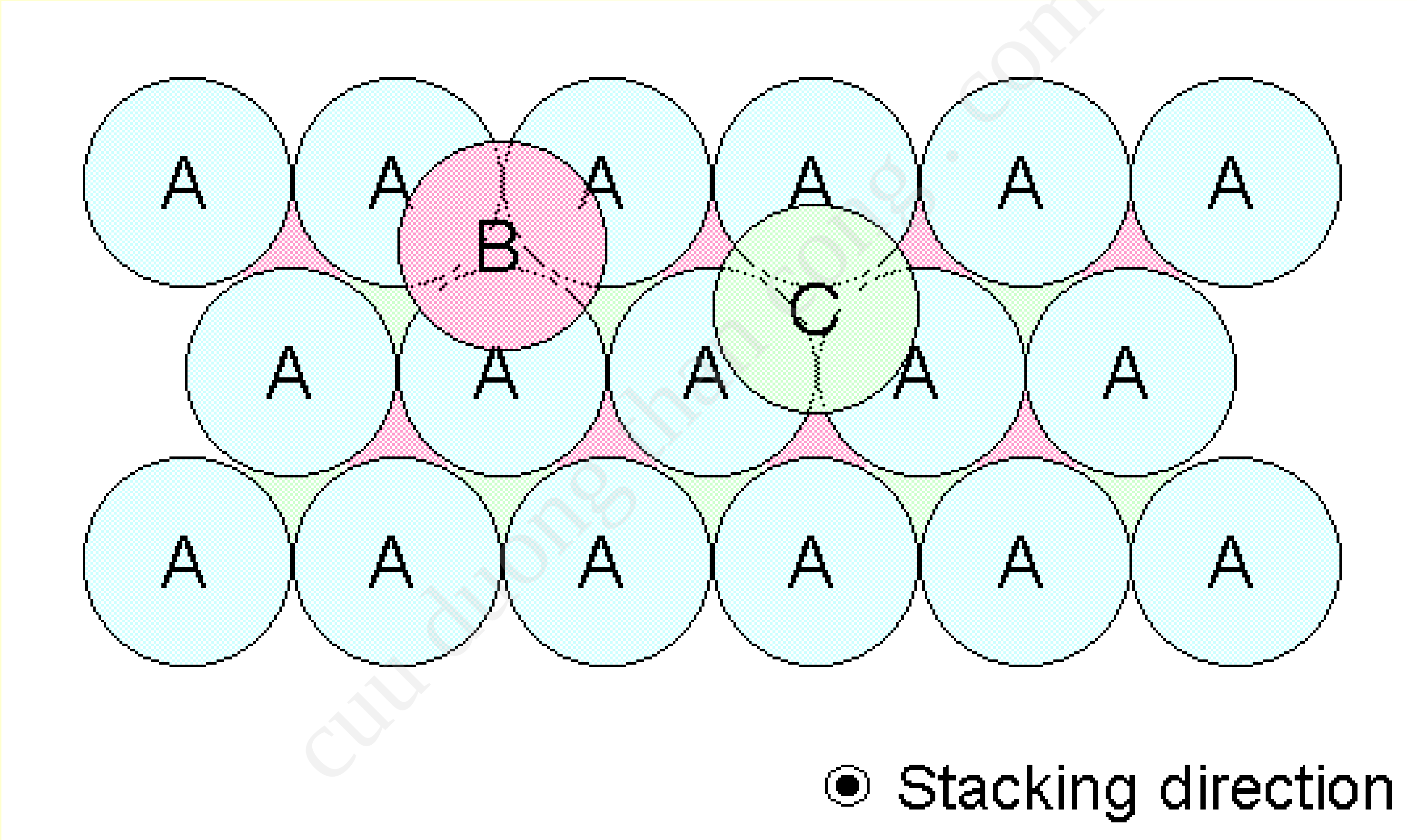
- Strong mechanical property, E=448 GPa (190GPa for Si)
- Chemical stability at high T
- Strong resistance to oxidation even at high T
- Passivation layer
- Wide bandgap even at 300K (2.996 at 300K, 3.03 at 0K for a-SiC)
- Single crystal, polycrystalline and amorphous can be formed by MOCVD, MBE, PECVD, etc.
- $SiH_4 + CH_4 \rightarrow SiC(s) + 4H_2$
- Doping, etching and metallization: possible but limited
- Good candidate for harsh environment MEMS

Material Properties of SiC

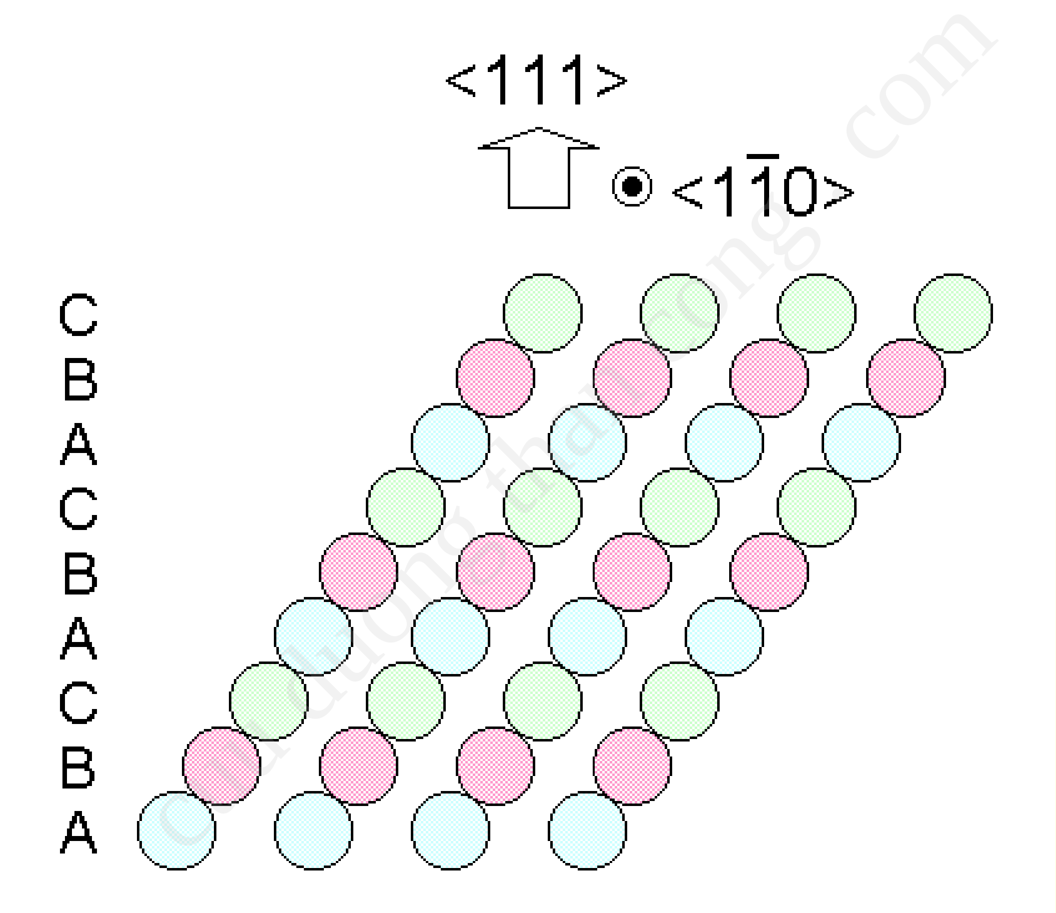
- 1-D polymorphism: polytypism
- Identical planar arrangement but with different stacking sequence
- Crystal structure: Cubic, Hexagonal, Rhombohedral
- 3C-SiC, 6H-SiC, 4H SiC



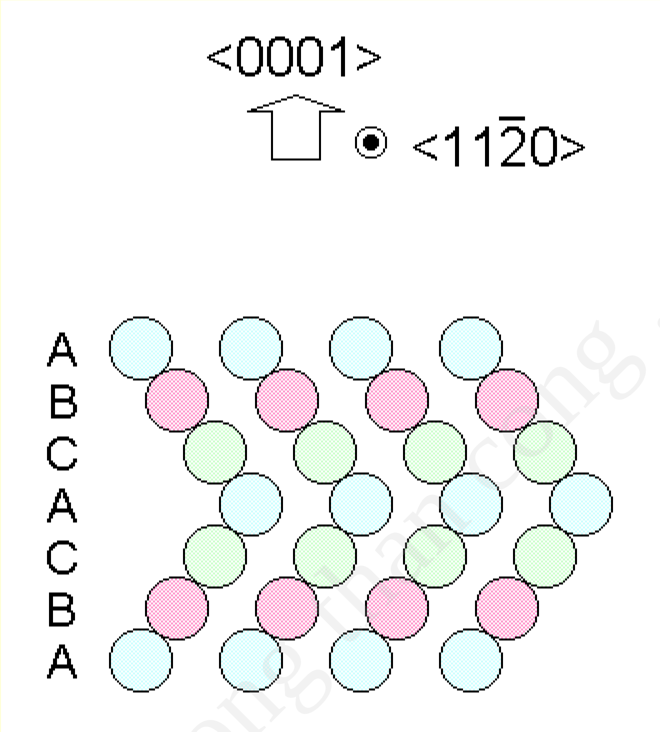
Stacking of planes



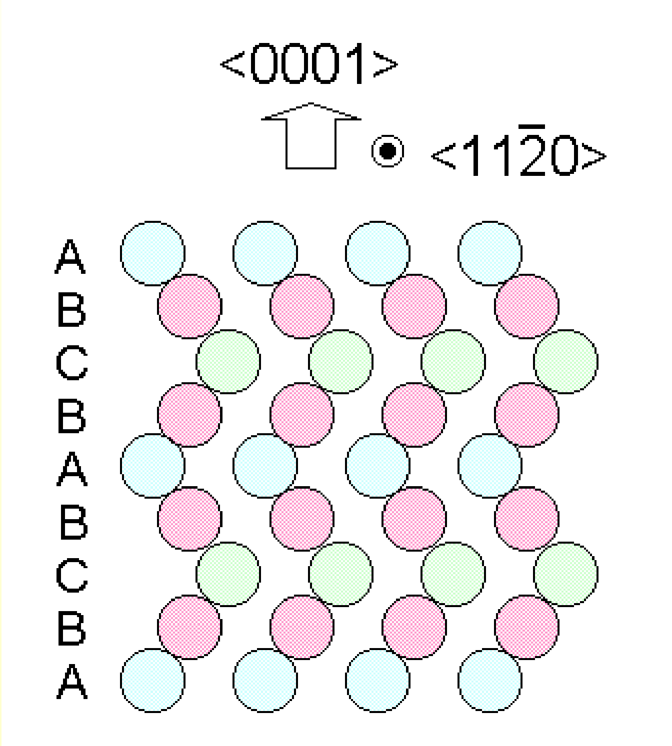
3C-SiC Structure



- 6H-SiC



- 4H-SiC



Property	3C-SiC	6H-SiC
Band Gap	2.2 eV	2.9 eV
Electron Mobility (cm^2/V sec)	1000	380
Hole Mobility (cm^2/V sec)	40	50
Saturation Drift velocity (10^7 cm/sec)	2.5	2
Breakdown voltage (MV/cm)	3	3-6

- Crystal growth

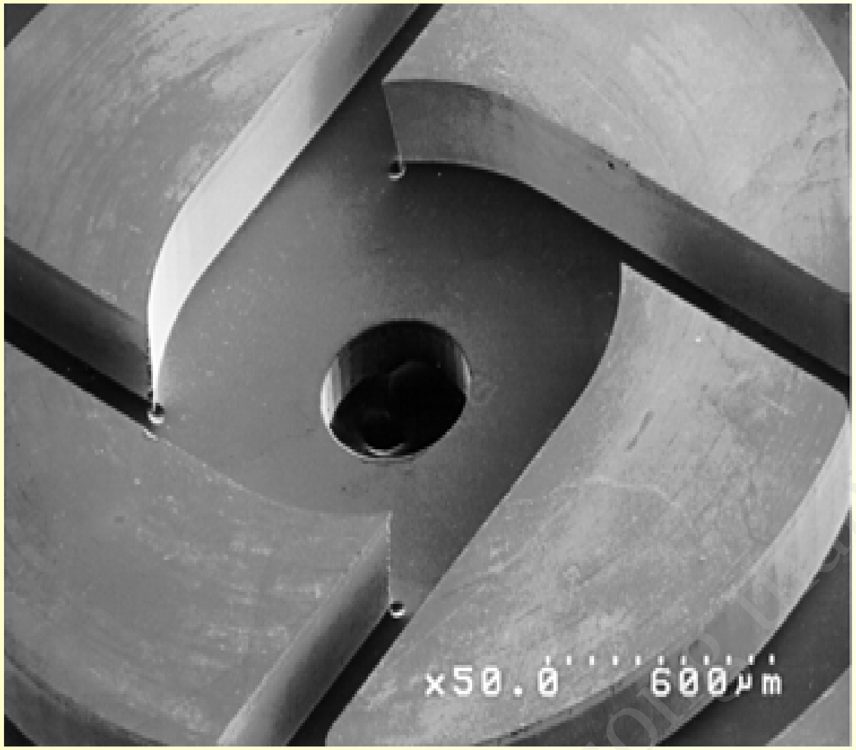
2-4” 6H-SiC can be grown with sublimation onto SiC seed at 2000°C

- Epitaxial growth

6H-SiC: APCVD with Silane and Propane source at 1500-1700°C over 6H-SiC

3C SiC: APCVD with Silane and Propane source at 1500-1700°C over Si → heteroepitaxy

Mismatch in lattice constant 0.436nm(SiC) and 0.543nm(Si) can be overcome with carbonization → convert near surface Si to 3C-SiC by heating and reaction with C → Grow 3C-SiC over carbonization layer



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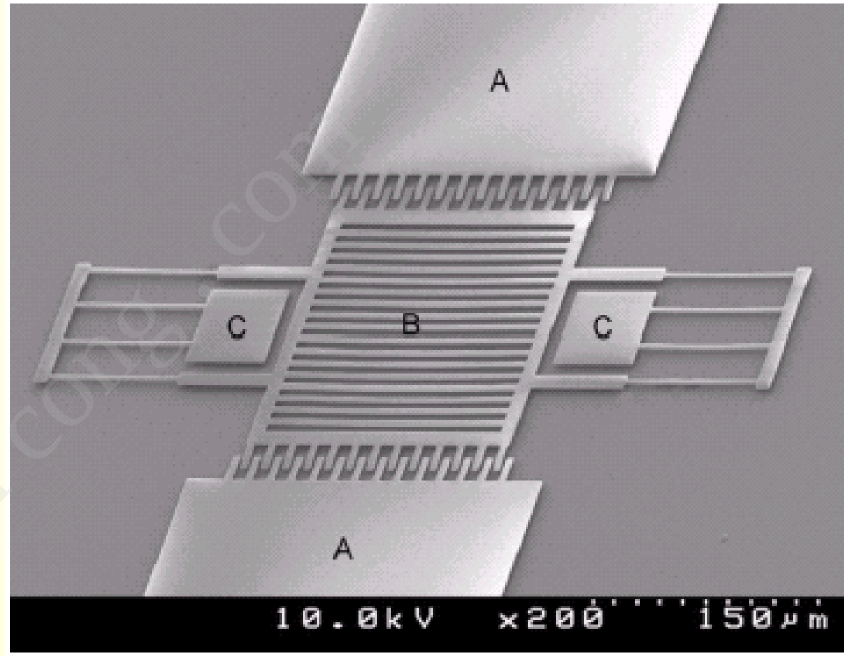

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Metal films

Metal	ρ ($\mu\Omega \cdot$ cm)	Typical Areas of Application
Ag	1.58	Electrochemistry
Al	2.7	Electrical interconnects
		Optical reflection in the visible and the infrared
Au	2.4	High temperature electrical interconnects
		Optical reflection in the infrared
		Electrochemistry
Cr	12.9	Intermediate adhesion layer
Cu	1.7	Low resistivity electrical interconnects
Indium-tin oxide (ITO)	300–3,000	Transparent conductive layer for liquid crystal displays
Ir	5.1	Electrochemistry
		Microelectrodes for sensing biopotentials
Ni	6.8	Magnetic transducing
NiCr	200–500	Thin film laser-trimmed resistor
Pd	10.8	Electrochemistry
		Solder wetting layer
Permalloy™ (Ni_xFe_y)	—	Magnetic transducing
Pt	10.6	Electrochemistry
		Microelectrodes for sensing biopotentials
SiCr	2,000	Thin film laser-trimmed resistor
SnO_2	5,000	Chemoresistance in gas sensors
TaN	300–500	Negative temperature coefficient of resistance (TCR)
		Thin film laser-trimmed resistor
Ti	42	Intermediate adhesion layer
TiNi	80	Shape-memory alloy, actuation
TiW	75–200	Intermediate adhesion layer
		Near zero temperature coefficient of resistance (TCR)
W	5.5	High temperature electrical interconnects

Organic materials

- Used increasingly for microfluidic and biochemical applications
- Light weight, easy processing, low cost, high electrical resistance, corrosion resistance, flexibility in engineering properties

- Photoresist
- Polyimide
- Parylene
- Conductive polymers
- PVDF (polyvinyldifluoride)
- PMMA(polymethylmethacrylate), PC(polycarbonate), PTFE(polytetrafluoroethylene), PDMS(polydimethylsilane)

- Teflon® - PTFE (Polytetrafluroethylene)
  - high chemical inertness
  - good thermal stability up to ~200°C
  - Extremely low friction coefficient
  - Thermoplastic
- Lexan® - PC (Polycarbonate)
  - High stiffness and strength
  - Thermal stability up to ~135 °C
  - High surface toughness and rigidity
  - Relatively low stability to chemical attack
- PEEK (Polyetheretherketone)
  - Excellent chemical resistance
  - Very high operating temperature ~ 250 °C
  - Good dimensional stability
  - Low moisture absorption even at elevated temperatures
  - High cost

- Kynar® - PVDF (polyvinyldifluoride)
  - Good chemical resistance
  - Thermal stablity upto ~ 140°C
  - High surface rigidity and strength
  - Virtually no absorption of water
- Ultem® - PEI (Polyetherimide)
  - Amorphous material
  - Material properties show small change over wide range of temperature
  - Excellent chemical resistance
  - Thermoplastic
  - Widely utilized for medical application
- PDMS (Polydimethylsiloxane); Silicone, RTV
  - Biocompatible and flexible
  - Low toxicity, No solvents or cure byproduct
  - Cures to a transparent, flexible elastomer
  - Low water adsorption
  - Stability over wide temperature range (from-55 to 200C)

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