

① Gochalski (G) method :-

typical Process Condition:-

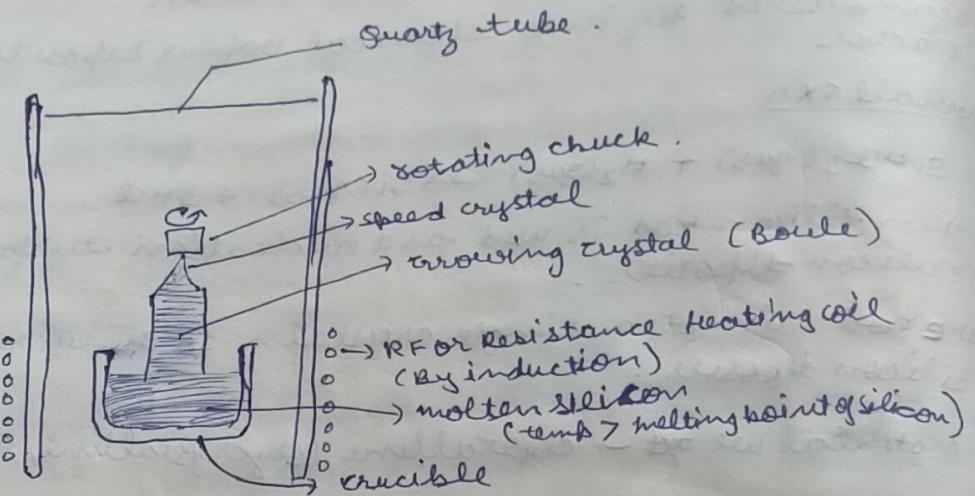
Flow Rate :- 20 to 50 Liters / min.

Time:- 18 to 24 hours

temp :- > 1500 degrees C.

pressure : 20 torr

[melting point of silicon = 1400]



factor which we can vary :-

- ① length of heater (can reduce fixed cost)
- ② rotating speed (depends diameter of growing crystal)

CZ crystal growing consists of the following steps:-

- ① A fused silica crucible is loaded with a charge of undoped EFG together with a precise amount of doped silicon. This determines the doping concentration of the resulting crystal.
- ② The gases inside the growth chamber are then evacuated.
- ③ Then filled with inert gases so as to avoid the formation of silicon oxides. As silicon easily gets oxygen from air and form silicon oxides.
- ④ The silicon charge inside the chamber is then melted. (Si melting point - 1420 deg C).
- ⑤ A slim seed of crystal silicon (5mm dia and 100-300 mm long) with precise orientation tolerances is introduced into the molten silicon. This determines the orientation of the resulting crystal.
- ⑥ The seed crystal is then withdrawn at a very controlled rate. This determines the diameter of the resulting crystal.
- ⑦ The seed crystal and the crucible are rotated in opposite directions while this withdrawal process occurs. This promotes mixing and more uniform growth.
- ⑧ Adverse effect of rotation -- increase corrosion of the crucible by the melts. Very few choices of crucible material relatively inert to the melts. Most used

④ mechanicallapping and chemical Polishing

0000)

The silicon ingot is grown and individual wafers are sliced.

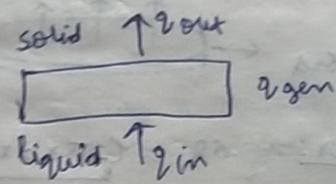
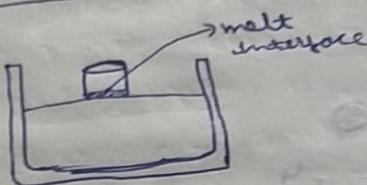


Cz crystal growth:

① how to control the diameter of the wafer?

② what is the maximum velocity of pulling the crystal from the melts?

calculation of v_p in Cz growth:-



$q_{gen} \rightarrow$ latent heat as liquid changes to solid then it ~~will~~ generate latent heat.

Assumption: ① No heat transfer

② thermophysical parameter $\rightarrow f(t)$

③ $\frac{dT}{dx} = 0 \Rightarrow V = v_p \rightarrow (cm/s)^2$

④ 1-d growth ($x \rightarrow 0$)

⑤ Interfacial dV - Same.

⑥ Convective heat transfer \rightarrow neglected.

⑦ $A \approx A_s \approx A_g$.

\rightarrow 1-d heat balance \rightarrow melt interface.

$$q_{in} + q_{gen} = q_{out}$$

$$-\kappa_f A_f \left. \frac{dT}{dx} \right|_L + (-L) \left. \frac{dm}{dt} \right|_L = -\kappa_s A_s \left. \frac{dT}{dx} \right|_S \xrightarrow{\text{solid interface}} \quad \left. \begin{array}{l} \\ \end{array} \right\}$$

$\xrightarrow{\text{liquid side interface}}$

$$\text{velocity } \frac{dm}{dt} = \rho A V_p \quad \left. \begin{array}{l} A \rightarrow \text{interface area} \\ \rho \rightarrow \text{density.} \end{array} \right\}$$

$\frac{dm}{dt}$ maximized when middle term is dropped.

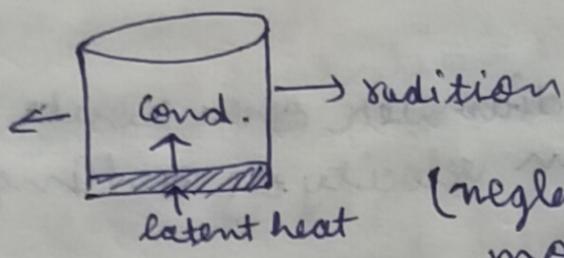
$$L \frac{dm}{dt} = \kappa_s A_s \left. \frac{dT}{dx} \right|_S$$

$$L(\rho A V_p) = \kappa_s A_s \left. \frac{dT}{dx} \right|_S \quad \left. \begin{array}{l} A \approx A_s \\ \end{array} \right\}$$

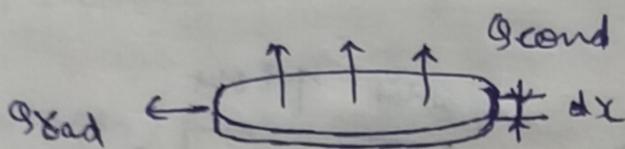
$$\Rightarrow V_p = \frac{\kappa_s}{L \rho} \left. \frac{dT}{dx} \right|_S$$

2) $k_s, L, N \rightarrow$ known // need to find $\frac{dT}{dx} \Big|_S$
 need to find . $T = T(x)$

Analysis:- slightly above the melt interface.



(neglect convection from molten silica).



Radiation:- $dQ = \underbrace{(2\pi x dx)}_{dA} \sigma \epsilon T^4 \quad \text{--- (1)}$

Conduction:- $\frac{dQ}{dx} = \cancel{2\pi x} (2\pi x) \sigma \epsilon T^4$

$$Q = k_s \pi r^2 \frac{dT}{dx}$$

$$\frac{dQ}{dx} = k_s \pi r^2 \frac{dT^2}{dx^2} + \pi r^2 \left(\frac{\partial T}{\partial x} \right) \left(\frac{\partial k_s}{\partial x} \right) \quad \text{--- (2)}$$

neglected $\cancel{c s \left(\frac{\partial s}{\partial x} \right) \times \left(\frac{\partial k_s}{\partial x} \right)}$ \rightarrow very small.

from (1) = (2)

$$(2\pi x dx) \sigma \epsilon T^4 = k_s \pi r^2 \frac{dT^2}{dx^2}$$

$$\frac{dT^2}{dx^2} = \frac{2\sigma \epsilon T^4}{k_s r} dx$$

$$\frac{d^2T}{dx^2} - \frac{2\sigma \epsilon T^4}{k_s r} = 0$$

- In order to eliminate the temperature gradient term we need to consider how the heat is conducted up the solid crystal and how it is eliminated from the solid.
- The latent heat of crystallization is transferred from liquid to the solid. This heat is then transported away from the freezing interface primarily by conduction up the solid crystal (B). The heat is lost from the crystal by radiation (C) and by convection, although we will consider only radiation to keep analysis simple.
- The thermal conductivity of silicon k_s varies approximately as $1/T$, at least for temperatures below about 1000°C using

$$k_s = k_m \frac{T_m}{T} *$$

where k_m is the thermal conductivity at the melting temperature T_m , we find that.

$$\frac{dT}{dx^2} - \frac{2\sigma \epsilon T^5}{k_m \times T_m} = 0$$

This differential equation has a solution given by

$$T = \left(\frac{3k_m \times T_m}{8\sigma \epsilon} \right)^{1/4} \sqrt{x + \left(\frac{3k_m \times T_m}{8\sigma \epsilon} \right)^{1/2}}$$

Differentiating this expression to find $\frac{dT}{dx}$, evaluating the result at $x = 0$ (the freezing interface) and substituting the result into , we have finally that

$$V_{\max} = \frac{1}{4\pi} \sqrt{\frac{2\sigma \epsilon k_m T_m^5}{3x}}$$

$$* \quad \sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$$

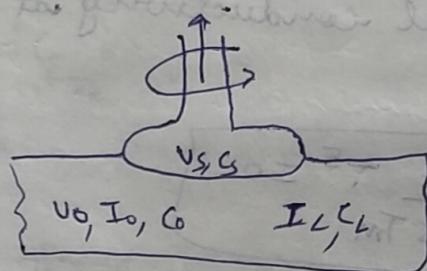
which is the desired result, showing that the maximum bulk rate is inversely proportional to the square root of the crystal radius.

* For c_2 growth, find expression of dopant concentration as a function of vol of the crystal solid.

→ we define V_0 , I_0 , and C_0 to be, respectively, the initial volume, number of impurities, and impurity concentration in the melt, V_L , I_L , and C_L to be, kept the volume, number and concentration of impurities in the melts during growth, and finally V_S and C_S to be the corresponding quantities in the solid crystal.

Note that V_L , I_L , C_L , V_S and C_S will all be function of time.
if $K_0 \neq 1$.

→ during the growth process, an additional volume of melts dV freezes, it will remove the melts a number of impurity given by.



$$dI = -K_0 C_L dV = -K_0 \frac{I_L}{V_0 - V_S} dV$$

$$\int_{I_0}^{I_L} \frac{dI}{I_L} = -K_0 \int_0^{V_S} \frac{dV}{V_0 - V_S}$$

$$\ln \left[\frac{I_L}{I_0} \right] = \log \left[1 - \frac{V_S}{V_0} \right]^{K_0}$$

$$I_L = I_0 \left(1 - \frac{V_S}{V_0} \right)^{K_0}$$

which gives the number of impurities in the melts as a function of how much of the melts has been frozen. C_S is the impurity concentration in the solid crystal when an incremental volume of the liquid freezes

$$C_S = -\frac{dI_L}{dV_S}$$

$$C_S = C_0 K_0 (1 - f)^{K_0 - 1}$$

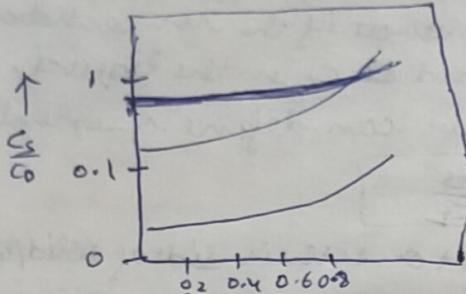


where $f = \frac{V_S}{V_0}$
The fraction frozen.

→ All impurities, whether they are intentional dopants or unwanted ~~so called segregations~~ trace elements, segregate b/w the liquid and solid phase when the two phases are in intimate contact. By this mean that if the concentration of the impurity are c_s in the solid and c_L in the liquid, then in general $c_s \neq c_L$. In fact we can define a segregation coefficient K_0 as follows
$$K_0 = \frac{c_s}{c_L}$$

c_s and c_L are the concentration just on either side of solid/liquid interface and K_0 is usually referred to as the equilibrium segregation coefficient. If $c_s > c_L$, the impurity prefers to be in the solid phase; if $c_s < c_L$, the reverse is true.
→ Segregation occurs because impurities have different solubilities in the two phases. The chemical potential of an impurity must be the same in the two phases across the interface and this result in segregation. K_0 values are normally experimentally measured quantities for a particular system at a particular temp. If the experimental conditions are far from equilibrium, then an effective value different from K_0 may be measured.

→ For silica $c_s > c_L$, this means that these impurities prefer to the liquid phase. If we start with a concn. c_L in the melt at the beginning of growth, then as the crystal grows, c_L will increase over time as the ~~at the~~ beginning silicon from the melt is incorporated into the growing crystal faster than the impurity is. The result will be a crystal that is doped more heavily toward the end of growth than it is at the beginning. In others words, both c_L and c_s will be functions of time during the growth and both will increase if $K_0 < 1$.



Fraction of melt

solidified.

→ The rotation of the crystal and the crucible during growth helps to minimize all these effects, but in real crystals, there are doping variations both radially and axially on microscopic and more macroscopic scales due to these non-idealities.

→ Radical doping variations also result from the fact that the freezing interface is actually concave into the melts, which ~~are~~ have also non-uniformity.

→ If ~~the~~ impurity / dopant concentration is to certain level then we can not use this and it is waste for company. therefore we maximum the ~~length~~ length through which there is ~~is~~ uniform concen. means concen. is less than threshold value.

Segregation effect in float-zone process:-

For most impurities in the liquid / solid silicon system, as we saw in the CZ case earlier, this means that most impurities prefer to the liquid phase. As the liquid zone sweeps up the polycrystalline rod, impurities will tend to stay in the liquid and be swept to the top of the rod. The resulting single crystal will have lower impurity levels than the starting rod. The process thus refines the material or improves its purity.

$$\text{where } C_L = \frac{I}{L}$$

↓ liquid

$$C_S = k_0 C_L \quad \left\{ k_0 = \frac{C_S}{C_L} \right\}$$

↓ solid.

$$C_0 = \frac{I_0}{L}$$

where: $I \rightarrow$ the number of impurities in the liquid.

$I_0 \rightarrow$ the " " " good uniformly at $t=0$

$C_0 \rightarrow$ concen. of " "

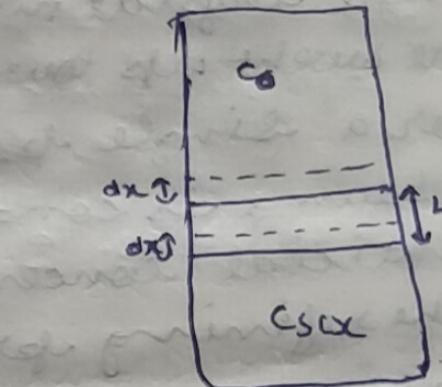
$$dI = (C_0 - C_S) dx$$

$$= (C_0 - k_0 C_L) dx$$

$$\int_0^I \frac{dI}{dx} = \int_{I_0}^I \frac{dI}{(C_0 - k_0 \frac{I}{L})}$$

$$x = -\frac{t}{k_0} \ln \left(\frac{C_0 - k_0 I/L}{C_0 - k_0 I_0/L} \right)$$

$$\frac{C_0 - C_{S(x)}}{C_0 (1 - k_0)} = e^{-\frac{k_0 x}{L}}$$



$$\left\{ C_{S(x)} = k_0 \frac{I}{L} \right\}$$

$$C_{S(x)} = C_0 \left[1 - (1 - k_0) e^{-\frac{k_0 x}{L}} \right] \star$$