Crystal Growth, Wafer Fab and Properties

• High Quality Single Crystal Wafers
• Diameter
• Thickness
• Flatness
• Mechanical defects (scratches)
• Crystallographic Defects (dislocation density)
• Crystal Orientation
• Impurity Level
• Dopant Type and Density-Resistivity
Silicon Structure Classification

- Single Crystal – periodic arrangement of atoms
- Polycrystalline – small crystals of arbitrary alignment
- Amorphous Silicon – no significant ordering of atoms

- Simple Crystal Unit Cells
  - Cubic
  - Body-Centered Cubic (extra atom in the body)
  - Face-Centered Cubic (extra atoms centered on faces)
Crystal Planes

- Planes and directions are defined using an x, y, z coordinate system.
  - [111] direction is defined by a vector having components of 1 unit in x, y and z.
- Planes are defined by Miller indices
  - Defined as the reciprocals of the intercepts of the plane with the x, y and z axes.

![Diagram of crystal planes](image-url)
Silicon Lattice

• Diamond cubic lattice
  – Two merged FCC lattices with the origin of the second offset from the first by $a/4$ in all three directions
  – Covalent bonding to four nearest neighbors

Figure 3-3 Diamond crystal structure of silicon. The unit cell may be visualized as two merged FCC cells, offset from each other by $a/4$ in all three directions. (a) shows the basic FCC unit cell. (b) shows two merged cells, offset by $a/4$. In (c), only the four atoms in the second FCC cell that lie within the first FCC cell are shown. The arrows show the corresponding $a/4$ displacement of these four atoms. In (d), the actual tetragonal bonding between the atoms in the diamond cell is shown.
Semiconductor Lattices

- 3D Model of unit cells for semiconductors
  
  http://jas.eng.buffalo.edu/education/solid/unitCell/home.html
  
  – from: http://jas.eng.buffalo.edu/index.html
  multiple semiconductor applets
Silicon Surface Plane Differences

• Bulk properties are generally isotropic with the symmetric lattice

• Dopant diffusion is independent as long as surfaces play no role in the process.
  – However, real devices are built near surfaces.
  – The plane that the surface terminates on can then make a difference.
  – [111] has the highest number of atoms per cm$^2$
  – [100] has the lowest (dominant type used)
  – Concerns:
    • Oxidation rates, surface defect density, “near” surface diffusion
Defects in Crystals

• Various types of defects can exist in crystal (or can be created by processing steps. In general these are detrimental to device performance.

Linear Defects:
Dislocation due to high stress or rapid thermal gradients

Volume Defects:
Agglomeration of point defects
Precipitate of dopants

Point Defects:
V missing/vacancy
I extra atom/interstitialcy

Dislocation
Precipitate
Stacking Fault
Stacking Fault

- Form along the {111} plane
  - The insertion or removal of an extra {111} plane
  - Normally referred to as ABCABC…
  - Extrinsic adds a plane ABCACBC… (excess interstitials)
    - Dominant type
    - Oxidation Induced Stacking Faults
  - Intrinsic if a plane is missing ABCABABC…
Raw Material and Purification

- **Raw Material** – Quartzite SiO$_2$
- **Convert Quartzite into metallurgical grade silicon or (MGS)**
  - Furnace with quartzite and carbon (coal or coke) @ 2000 °C
  - ~ 98% pure
    \[
    2C(solid) + SiO$_2$(solid) \rightarrow Si(liquid) + 2CO
    \]
- **MFGS converted to electronics grade silicon (EGS)**
  - MGS powder combined with gaseous HCl
  - Produce SiH$_4$ (silane), SiH$_3$Cl (chlorosilane), SiH$_2$Cl$_2$ (dichlorosilane), SiHCl$_3$ (trichlorosilane), or SiCl$_4$ (silicon tetrachloride)
Raw Material and Purification (2)

• SiHCl$_3$ (trichlorosilane) processing
  – Room temperature liquid that can be purified using fractional distillation. Boiled and condensed back into a liquid.

• Chemical vapor deposition
  – SiHCl$_3$ (gas) and hydrogen (gas) with Si rod

\[
2\text{SiHCl}_3(gas) + 2\text{H}_2(gas) \rightarrow 2\text{Si}(solid) + 6\text{HCl}(gas)
\]
  – Deposition of polysilicon (parts per billion purity)
    \(10^{13}\) to \(10^{14}\) cm$^{-3}$ impurities

• Polysilicon used for either:
  – Czocharski (CZ) crystal growth
  – Float-Zone (FZ) crystal growth
Crystal Growth

• The raw material contains < 1 ppb impurities. Pulled crystals contain O ($\approx 10^{18} \text{ cm}^{-3}$) and C ($\approx 10^{16} \text{ cm}^{-3}$), plus any added dopants placed in the melt.

• Essentially all Si wafers used for ICs today come from Czochralski (cho-HRAL-skee) grown crystals.

• Polysilicon material is melted, held at close to 1417 °C, and a single crystal seed is used to start the growth.

• Pull rate, melt temperature and rotation rate are all important control parameters.

• Approximately $50 per 8 \text{ in.} \text{ wafer when text written}$
Crystal Growth (2)

(More information on crystal growth at http://www.memc.com)

(Photo courtesy of Ruth Carranza.)
Float Zone Crystal Growth

- An alternative process is the float zone process which can be used for refining or single crystal growth.
- Localized I^{2}R heating via RF Coil
  - Nitrogen or dopant ambient
- Wafers < 150 mm
  - Detectors and power
  - Doping is a challenge
  - Reduced C and O impurities
- Bottom in contact with single crystal seed
Silicon Wafer Diameter

http://www.semiconductor.net/article/205503-The_Next_Wafer_Diameter_Change.php
Ingot Cutting into Wafers

After crystal pulling, the boule is shaped and cut into wafers which are then polished on one side.

(See animations of crystal polishing etc. at http://www.memc.com)
Wafer Preparation and Specification

Mark wafer earlier (laser process) to track their process flow.

- Grind crystal to a diameter (200mm ⇔ 750µm) ... 850µm thick
- Grind flats (the primary and secondary)
- Saw of the boule into wafers
- Lapping, etching (batch process in acids etching Si) 20 µm, polishing (chemical-mechanical) 25µm removes damage and improves flatness ±2µm

Suspension

$\text{Al}_2\text{O}_3$

$\text{SiO}_2$ 10nm in NaOH/DI

CMP

$3\text{Si} + 4\text{HNO}_3 + 18\text{HF} \Rightarrow 3\text{H}_2\text{SiF}_6 + 4\text{NO} + 8\text{H}_2\text{O}$

Figure 3-8 The upper figures were taken directly from the Silicon Database on the Mitsubishi Materials Silicon Corporation web site at www.egg.or.jp/MSII/english/index-e.html. They conceptually illustrate the wafer polishing operation. An actual machine is shown below. Photo courtesy of R. Carranza.
MEMC Process Animation

• Crystal Pulling
• Rod Grinding
  – Achieving the correct diameter
  – Grinding flats for crystal orientation
• Wire Cutting
  – 100 mm, 150 mm, 200 mm, 300 mm, 450 mm
• Edge Profiling
• Lapping
  – Improve wafer flatness
• Etching and Polishing
• Laser Inspection
Measurement Methods

- Sheet Resistance
  - Co-linear four-point probe
  - Van der Pauw
- Hot Point Probe
- Hall Effect
Measurements of the Grown Crystal

Resistivity

\[ \rho = \frac{1}{q \mu_n n + q \mu_p p} \text{[\(\Omega\text{cm}\)]} \]

\[ V = \frac{\rho I}{2\pi r} \]

\[ \rho = 2\pi s \frac{V}{I} \text{[\(\Omega\text{cm}\)]} \]

\[ \rho = \frac{\pi t}{\ln(2)} \frac{V}{I} = 4.532 \frac{V}{I} x_j \text{[\(\Omega\text{cm}\)]} \]

\[ \rho_s = \frac{\rho}{x_j} = \frac{\pi}{\ln(2)} \frac{V}{I} = 4.532 \frac{V}{I} \text{[\(\Omega\text{/square}\)]} \]
Measurements of the Grown Crystal

Conductivity Type

Seebeck voltage

Electrons move - Donors stay

\[ J_n = qn\mu_n P_n \frac{dT}{dx} \]

25-100°C hotter

Sign of the voltage V tells what is the conductivity type
Hall Effect Measurement

Measurements of majority carrier concentrations (and type) and their mobility

\[ \rho = \frac{w \cdot \mu}{I_x} \] w/o B field

Test structure

Electrons at the bottom

Figure 3-13 Conceptual representation of Hall effect measurement. The right sketch is a top view of a more practical implementat

Force = \( Q(\varepsilon + v \times B) \)

\[ F_y = q(\varepsilon_y + v_x B_z) = 0 \]

\[ \varepsilon_y = -B_z v_x = B_z \frac{I_x}{q \mu} \]

\[ V_y = B_z \frac{I_x}{q \mu n} \]

\[ R_H = \frac{t V_y}{B_z I_x} \]

\[ \rho, n = \pm \frac{1}{q R_H} \]

\[ \mu_H = \frac{|R_H|}{\rho} = |R_H| \sigma \]
Measuring Impurities

**Fourier Transport Infrared Spectroscopy (FTIR)**

For Interstitial Oxygen incorporated during CZ growth and Substitutional Carbon (detection limit O- $2 \times 10^{15} \text{cm}^{-3}$, C- $5 \times 10^{15} \text{cm}^{-3}$)

Fourier transform

Sweep the wavelength of incident energy $\rightarrow$ look for absorption

![FTIR experimental apparatus diagram](image)
SEM and TEM

• Scanning Electron Microscope
  - Large depth of focus
  - Magnification 300,000x
  - Resolution below 5 nm

• Transmission Electron Microscope
  - Prepared samples
    (1 um thickness)
  - Resolution is about 0.2 nm

Figure 3-15 TEM image of the Si/SiO₂ interface. The crystalline structure of the silicon is visible on the bottom. The thermally grown SiO₂ is amorphous. Photo courtesy of John Bravman, Stanford University.
Models and Simulation

- Czochralski Crystal Growth
- Dopant Incorporation in CZ
- Zone Refining and FZ Growth
- Point Defects
- Oxygen in Silicon
- Carbon in Silicon
Modeling Crystal Growth

- We wish to find a relationship between pull rate and crystal diameter.
- Freezing occurs between isotherms $X_1$ and $X_2$.
- Heat balance:
  - latent heat of crystallization + heat conducted from melt to crystal = heat conducted away.

\[
L \frac{dm}{dt} + k_L \frac{dT}{dx_1} A_1 = k_s \frac{dT}{dx_2} A_2
\]
Model Crystal Growth (2)

- The rate of growth of the crystal is where $v_P$ is the pull rate and $N$ is the density and $A$ the cross sectional area.

- Neglecting the middle term in Eqn. (1) we have:

$$\frac{dm}{dt} = v_P \cdot A \cdot N$$

(2)

$$L \frac{dm}{dt} \leq k_S \frac{dT}{dx_2} A_2$$

$$v_P \cdot A \cdot N \cdot L \leq k_S \frac{dT}{dx_2} A_2$$

$$v_{PMAX} = \frac{k_S}{L \cdot N} \frac{dT}{dx_2}$$

(3)
Model Crystal Growth (3)

- In order to replace $dT/dx^2$, we need to consider the heat transfer processes.
- Latent heat of crystallization (A) transfers up the crystal (B) and is lost by radiation (C).

- Heat radiation from the crystal (C) is given by the Stefan-Boltzmann law
  \[ dQ = (2\pi r dx) \cdot (\sigma \varepsilon T^4) \]  
  (4)

- Heat conduction up the crystal is given by
  \[ Q = k_s (\pi \cdot r^2) \cdot \frac{dT}{dx} \]  
  (5)

- Differentiating (5), we have
  \[ \frac{dQ}{dx} = k_s (\pi r^2) \frac{d^2T}{dx^2} + (\pi r^2) \frac{dT}{dx} \frac{dk_s}{dx} \approx k_s (\pi r^2) \frac{d^2T}{dx^2} \]  
  (6)
Model Crystal Growth (4)

• Substituting (6) into (4), we have

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

(7)

• \(k_S\) varies roughly as \(1/T\), so if \(k_M\) is the thermal conductivity at the melting point,

$$k_S = k_M \frac{T_M}{T}$$

(8)

$$ \therefore \frac{d^2T}{dx^2} - \frac{2\sigma\varepsilon}{k_M r T_M} T^5 = 0$$

(9)

• Solving this differential equation, evaluating it at \(x = 0\) and substituting the result into (3), we obtain

$$T = \left(\frac{3k_M r T_M}{8\sigma\varepsilon}\right)^{\frac{1}{4}} \cdot \left( x + \left( \frac{3k_M r}{8\sigma\varepsilon T_M^3} \right)^{\frac{1}{2}} \right)^{-\frac{1}{2}}$$

$$v_{MAX} = \frac{1}{LN} \sqrt{\frac{2\sigma\varepsilon k_M T_M^5}{3r}}$$

(10)

• Using the example on p. 124, this gives a max pull rate of \(\approx 24 \text{ cm hr}^{-1}\) for a 6” crystal (Actual values are \(\approx 2X\) less than this).
Monitoring Ingot Growth

- Automation of the process incorporates numerous sensors and feedback
  - Optical monitoring of resulting crystal diameter
  - Infrared sensing of temperature
  - Thermocouples for specific temperatures within chamber
Modeling Dopant Behavior During Crystal Growth

• Dopants are added to the melt to provide a controlled N or P doping level in the ingot and resulting wafers.

  – The dopant incorporation process is complicated by dopant segregation, a difference in the impurity concentration between the liquid and solid.

  – Segregation occurs between the liquid and solid phase of material when they are in intimate contact. An experimentally measured segregation coefficient defines the difference between the two.

  $$k_o = \frac{C_s}{C_L}$$
# Segregation Coefficient

\[ k_O = \frac{C_S}{C_L} \]

<table>
<thead>
<tr>
<th>Dopant</th>
<th>( k_O )</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>0.3</td>
</tr>
<tr>
<td>Bi</td>
<td>7 \times 10^{-4}</td>
</tr>
<tr>
<td>C</td>
<td>0.07</td>
</tr>
<tr>
<td>Li</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>O</td>
<td>0.5</td>
</tr>
<tr>
<td>P</td>
<td>0.35</td>
</tr>
<tr>
<td>Sb</td>
<td>0.023</td>
</tr>
<tr>
<td>Al</td>
<td>2.8 \times 10^{-3}</td>
</tr>
<tr>
<td>Ga</td>
<td>8 \times 10^{-3}</td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
</tr>
<tr>
<td>Au</td>
<td>2.5 \times 10^{-5}</td>
</tr>
</tbody>
</table>

- Most \( k_O \) values are <1; therefore, the impurity prefers to stay in the liquid.
- Thus as the crystal is pulled \( C_L \) increases.
- As the melt concentration increases, the silicon crystal doping, \( N_S \), will also increase.
Dopant Model

- If during growth, an additional volume $dV$ freezes, the impurities ($I$) incorporated into the volume $dV$ are given by

$$dI = -k_0 C_L dV = -k_0 \frac{I_L}{V_O - V_S} dV$$

(12)

$$I_L = I_O \left(1 - \frac{V_S}{V_O}\right)^{k_0}$$

(14)

- This equations defines the number of impurities in the melt as a function of how much of the melt has solidified.
Dopant Model (2)

- Knowing the number of impurities in the melt as a function of how much of the melt has solidified. We define the fraction of melt “frozen” as \( f \).

\[
f = \frac{V_S}{V_0} = I_L = I_O (1 - f)^{k_o}
\]

- The impurities in the crystal \((C_S)\) can then be computed using:

\[
C_S \propto -\frac{dI_L}{dV_S} \quad \text{(15)}
\]

\[
C_S = C_O k_O (1 - f)^{k_o - 1} \quad \text{(16)}
\]

- This equations defines expected impurity concentration in the resulting wafers based on their location in the crystal. This is directly related to the amount of melt solidified in the ingot pulling process, \( f = 0 \) to \( f = 1 \).
Doping Concentration vs. Position

- Plot of Eq. (16).

- Note the relatively flat profile produced by boron with a $k_S$ close to 1.

- Dopants with $k_S << 1$ produce much more variation in doping concentration along the crystal.
Float Zone Growth and Refining

RF -> melt zone moving

Poly-Si

CO original concentration in the rod

dx

dI=(C_0-k_0C_L)dx

I - impurities in the liquid

- In the float zone process, dopants and other impurities tend to stay in the liquid; therefore, refining can be accomplished, especially with multiple passes

- See the text for models of this process.

\[
C_S(x) = C_O \cdot \left\{ 1 - \left(1 - k_O\right) \cdot e^{-\frac{k_O \cdot x}{L}} \right\}
\]
**FZ Impurity Behavior**

*Figure 3-20* Behavior of impurities during float-zone growth or zone refining. The solid is assumed to start with a uniform doping concentration $C_0$. The curves correspond to one pass of the molten zone through the solid.

*Figure 3-21* Zone refining with multiple passes. $k_0 = 0.1$ in this example.
Modeling Point Defects

• Vacancies (V) and Interstitials (I)
• The existence of defects minimizes the total free energy of the crystal. Therefore, they will exist for all temperatures above absolute zero.
  – The concentrations can be related as

\[
C_{I0}^* , C_{V0}^* = N_S \exp\left(\frac{S_f^*}{k}\right) \exp\left(\frac{-H_f^*}{kT}\right)
\]

  – \(S_f^*\) is the formation entropy of the defect
  – \(H_f^*\) is the enthalpy of formation of the defect
  – \(N_S\) is the number density of lattice sites
  – \(^*\) denotes equilibrium
Point Defect Equilibrium

- The Frenkel process: moving a silicon atom off from a lattice site inside a crystal. It creates equal number of V and I.
- I created if silicon atom moves from the surface into the bulk.
- V and I can be recombined removing one of each
- Stacking fault can capture either V or I by growing or shrinking but one lattice site
- In general, there is an assumption that the equilibrium population rate of change is due to kinematics and is assumed to change “immediately” with respect to temperature.
  - With the exception of ion implantation and CZ growth

- Estimated values for Silicon
  
  $$C_{I^0}^* \approx 1 \times 10^{27} \exp\left(-\frac{3.8eV}{kT}\right)$$
  $$C_{V^0}^* \approx 9 \times 10^{23} \exp\left(-\frac{2.6eV}{kT}\right)$$
Concentration Example

- At 1000 °C

\[ C_{I0}^* \approx 1 \times 10^{12} \text{ cm}^{-3} \]
\[ C_{V0}^* \approx 5 \times 10^{12} \text{ cm}^{-3} \]
\[ k \approx 8.617343 \times 10^{-5} \text{ cm}^{-3} \]
\[ n_i \approx 7.14 \times 10^{18} \text{ cm}^{-3} \]
\[ N_D, N_A \approx 10^{15} \text{ to } 10^{20} \text{ cm}^{-3} \]

Defects are present but concentrations significantly less than carriers and difficult to detect.
Point Defect Diffusivities

- Point defects are extremely mobile.
  - Crystal kinematics.
  - Not directly measured, but has been inferred from dopant diffusivity.

\[
d_I \approx 51 \exp\left(\frac{-1.8eV}{kT}\right) \text{cm}^2 \cdot \text{sec}^{-1}
\]

\[
d_V \approx 3.65 \times 10^{-4} \cdot \exp\left(\frac{-1.58eV}{kT}\right) \text{cm}^2 \cdot \text{sec}^{-1}
\]
Modeling Point Defects in Silicon

- Point defects (V and I) will turn out to play fundamental roles in many process technologies.
- The total free energy of the crystal is minimized when finite concentrations of these defects exist.

In general, $C_{I0}^* \neq C_{V0}^*$ and both are strong functions of temperature.

- Kinetics may determine the concentration in a wafer rather than thermodynamics.
Charged Point Defects

• Shockley and Last (1957) first described these charged defect concentrations.

• V and I also exist in charged states with discrete energies in the Si bandgap.
  – In N type Si, \( V^- \) and \( V^- \) will dominate.
  – In P type, \( V^+ \) and \( V^{++} \) will dominate.

\[
\begin{array}{c|c|c}
\hline
\text{E}_F \text{ for an N type material} & \text{E}_C & \text{I} \\
\hline
\text{E}_F - & - & \text{E}_C - E_{V^-} & 0.57 \text{ eV} \\
\text{E}_i - & - & \text{E}_C - E_{I^-} & 0.3 \text{ eV} \text{ ??} \\
\text{V}^+ & \text{E}_V & \text{E}_C - E_{V^-} & 0.11 \text{ eV} \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c}
\hline
\text{E}_V & \text{E}_C - E_V & \text{E}_C - E_{I^+} & 0.4 \text{ eV} \text{ ??} \\
\hline
\text{E}_{V^{++}} & \text{E}_V & \text{E}_{I^{++}} - E_V & \text{E}_{I^{++}} - E_V & \text{??} \\
\text{I} & \text{??} & \text{??} \\
\hline
\end{array}
\]

Table 3–3: Estimated energy levels of \( V \) and \( I \) energy levels in the silicon bandgap.

[3.6]. The question marks indicate values that are unknown or uncertain.
Charged Point Defects

• For intrinsic silicon, no change in charge occupation.
• For extrinsic N type Si, $V^=$ and $V^-$ will dominate as the Fermi energy rises.
  – The dominant vacancy charge state becomes $V^-$ acting like an acceptor.
• For extrinsic P type Si, $V^+$ and $V^{++}$ will dominate. As the Fermi energy falls.
  – The dominant vacancy charge state becomes $V^{++}$ acting like an donor.

\[
\begin{align*}
E_F & \quad E_i \\
\hline
\hline
V^= & \quad E_C \\
V^- & \quad E_F \quad \text{for an N type material}
\end{align*}
\]

\[
\begin{align*}
V^+ & \quad 28 \\
V^{++} & \quad E_V
\end{align*}
\]
Charge Defect Concentrations

Shockley and Last (1957) first described these charged defect concentrations (see text).

\[
C_{V^+}^* = C_{V^0}^* \exp \left( \frac{E_{V^+} - E_F}{kT} \right)
\]

\[
C_{V^-}^* = C_{V^0}^* \exp \left( \frac{E_F - E_{V^-}}{kT} \right)
\]

Note:
- The defect concentrations are always \( \ll n_i \). (doping \( \rightarrow \) \( E_F \rightarrow \) point defect concentrations)
- As doping changes, the neutral point defect concentrations are constant.
- However, the charged defect concentrations change with doping.

\( \therefore \) the total point defect concentrations change with doping.
Point Defect Example

- At 1000 °C, the P region will be intrinsic, the N region is extrinsic.
- $E_g \approx 0.7778$ eV
- Compute $n_i$ and check $N_D$ and $N_A$
- Construct energy band diagram

Intrinsic:
- Fermi Level in middle

Extrinsic:
- Fermi Level shifted

Figure 3-24 Calculated bandgap, point defect energy levels and Fermi levels at 1000°C.
Point Defect Example

- Compute $V_0$ and $I_0$
- Compute P-type $V$ and $I$

Note:
- $n_i$ relative to doping in the two regions.
- $V_0$ is the same in the two regions.
- Different charge states dominate in the different regions.

<table>
<thead>
<tr>
<th></th>
<th>P Region</th>
<th>N Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping</td>
<td>$1 \times 10^{15}$ cm$^{-3}$</td>
<td>$5 \times 10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$n_i$</td>
<td>$7.14 \times 10^{18}$ cm$^{-3}$</td>
<td>$7.14 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$V_0$</td>
<td>$4.6 \times 10^{13}$ cm$^{-3}$</td>
<td>$4.6 \times 10^{13}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$V^-$</td>
<td>$2.37 \times 10^{14}$ cm$^{-3}$</td>
<td>$1.61 \times 10^{15}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$V^=$</td>
<td>$1.85 \times 10^{13}$ cm$^{-3}$</td>
<td>$8.50 \times 10^{14}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$V^+$</td>
<td>$2.08 \times 10^{12}$ cm$^{-3}$</td>
<td>$3.06 \times 10^{11}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$V^{++}$</td>
<td>$1.94 \times 10^{11}$ cm$^{-3}$</td>
<td>$4.23 \times 10^{9}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$I_0$</td>
<td>$9.13 \times 10^{11}$ cm$^{-3}$</td>
<td>$9.13 \times 10^{11}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$I^-$</td>
<td>$4.02 \times 10^{11}$ cm$^{-3}$</td>
<td>$2.73 \times 10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$I^+$</td>
<td>$8.32 \times 10^{10}$ cm$^{-3}$</td>
<td>$1.48 \times 10^{11}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>
Oxygen and Carbon in CZ Silicon

- The CZ growth process inherently introduces O and C.

- Typically, \( C_O \approx 10^{18} \) cm\(^{-3} \) and \( C_C \approx 10^{16} \) cm\(^{-3} \).

- The O in CZ silicon often forms small SiO\(_2\) precipitates in the Si crystal under normal processing conditions.

- O and these precipitates can actually be very useful.
  - Provide mechanical strength.
  - Internal gettering (described later in Chapter 4).
Summary of Key Ideas

• Raw materials (SiO2) are refined to produce electronic grade silicon with a purity unmatched by any other commonly available material on earth.
• CZ crystal growth produces structurally perfect Si single crystals which can then be cut into wafers and polished as the starting material for IC manufacturing.
• Starting wafers contain only dopants, O, and C in measurable quantities.
• Dopant incorporation during crystal growth is straightforward except for segregation effects which cause spatial variations in the dopant concentrations.
• Point, line, and volume (1D, 2D, and 3D) defects can be present in crystals, particularly after high temperature processing.
• Point defects are "fundamental" and their concentration depends on temperature (exponentially), on doping level and on other processes like ion implantation which can create non-equilibrium transient concentrations of these defects.