Minimize Parasitic Resistive Losses

- Both shunt and series resistance losses decrease fill factor and efficiency
- Low shunt resistance is a processing defect rather than a design parameter
- Series resistance controlled by the top contact design and emitter resistance needs to be carefully designed

Top Contacts

- Metallic top contacts are necessary to collect the current generated by the solar cell
- Bus Bars are connected directly to the external leads
- Fingers are finer areas of metal that collect the current and delivers it to the bus bars
- Trade-off between resistive losses and reflection losses

Base Resistance

- Generated current flows perpendicular to surface from the bulk, then laterally in the emitter
- Resistance is assumed isotropic
- Bulk Resistance:
  \[ R_b = \frac{\rho_{\text{bulk}} \cdot w}{A} \]
  \[ \rho_{\text{bulk}} = \text{Bulk Resistivity (0.5 - 5 \( \Omega \)-cm)} \]
  \[ w = \text{Width of Bulk Region} \]
  \[ A = \text{Area of Solar Cell} \]

Sheet Resistivity

\[ R = \frac{\rho \cdot L}{A} = \frac{\rho_s \cdot L}{t \cdot w} = \frac{\rho_s \cdot L}{t \cdot w^2} \]

\[ \rho_s = \text{Sheet Resistivity} \]
\[ \rho = \text{Resistivity of the layer} \]
\[ t = \text{Thickness of the layer} \]
Non-uniform Films

$$\rho_s = \frac{1}{\int_0^1 \rho(x) dx} = \frac{1}{\int_0^1 q(x) dx}$$

Net Dopant concentration

Distance from surface

p-type region

Typically a gaussian function

Typically a gaussian function

Emitter Resistance

- The emitter resistance can be calculated as a function of the finger spacing in the top contact
- The path length of the current flow is not constant
  - Shortest near the finger
  - Longest at the midpoint between fingers

Calculation

$$dP_{loss} = I'dR$$
$$dR = \frac{\rho_s}{b} dy$$
$$I(y) = Jb y$$
$$P_{loss} = \frac{1}{2} (Jb y)^2 \frac{\rho_s}{b} dy$$
$$P_{loss} = J^2 b \rho_s s^3$$
$$= \frac{24}{24}$$
$$= (0.3 m^2) (100 \times 10^3)$$
$$= 0.0003 (W)$$

4-point Probe

$$\rho = 2\pi \frac{V}{I} (t >> s)$$
$$\rho = \frac{\pi i V}{\ln 2 I} (s >> t)$$
$$\rho_s = \frac{V}{I} = 4.53 \frac{V}{I}$$

The typical sheet resistivity for the emitter in silicon solar cells is 30-100 \Omega/□.

Idealized Current Flow

Current increases linearly with y

Fractional Power Loss

$$P_{cond} = J_{s}^2 b \rho_s s^3$$
$$P_{loss} = \frac{P_{cond}}{12} = \frac{J_{s}^2 b \rho_s s^3}{12 V_{sp}}$$

For a lateral resistance loss of less than 4%:

$$4\% < \frac{\rho_s s^3 J_{s}}{12 V_{sp}} = \frac{(40 \Omega/cm^2)(0.3 m^2)}{12(0.5 V)} \Rightarrow s \leq 0.42 cm$$
Contact Resistance

- Occur at the interface between the silicon and the metal
- Heavily doped to reduce contact resistance
- Trade off with efficiency
- Excess phosphorus at the surface creates a dead layer where photogenerated carriers have little chance of being collected → poor blue response

Contact Doping

Metal Grid Pattern

- Minimize losses associated with the top contact
  - Resistive losses in the emitter
  - Resistive losses in the metal top contact
  - Shading losses from the metal pattern

Grid Pattern Emitter Resistance

- Power loss from the emitter resistance goes as the cube of the finger spacing
- A short distance between fingers is desirable for low emitter resistance

Grid Resistance

- Determined by:
  - The resistivity of the metal used to make the grid
  - The pattern of the metal
  - The aspect ratio of the metal
- A low resistivity and high aspect ratio are desirable but typically limited by the fabrication technology

Shading Losses

- Caused by the presence of metal on the top surface of the solar cell that prevents light from entering the solar cell
- Determined by the transparency of the top surface
  - Fraction of the top surface covered by metal
- Practical limited by the minimum linewidth for a fabrication technology
- For identical transparency, a narrow linewidth technology can have finer lines and closer finger spacing resulting in lower emitter losses
Design Rules

- The optimum width of the busbar (WB) occurs when the resistive loss in the busbar equals its shadowing loss.
- A tapered busbar has lower losses than a busbar with constant width.
- The smaller the unit cell, the smaller the finger width (WF) and the smaller the finger spacing (s) the lower the loss.

Design Compromises

- Substrate
- Cell Thickness
- Doping of Base
- Reflection of Base
- Emitter Thickness
- Doping Level of Emitter
- Grid Pattern
- Rear Contact

Substrate Material

- Silicon dominates the market
  - Piggybacks the Integrated Circuit (IC) industry
  - Abundant
  - Relatively Inexpensive
- Silicon is not optimal
  - Band gap is slightly too low
  - Indirect band gap → low absorption coefficient
    - Overcome by light trapping
    - Difficult to grow into thin sheets

Cell Thickness

- Typically 100-500 μm
- Optimal solar cell with light trapping and very good surface passivation gives 100 μm thickness
- Usually 200-500 μm due to practical issues such as wafer durability and handling but also for surface passivation reasons

Doping of Base

- Typically near 1 Ω-cm
- A higher base doping leads to higher V_{OC} and lower resistance
- But high doping levels result in crystal damage

Electron and Current Flow in Solar Cells

Reflection Control

- Front surface typically textured
- Antireflection layers can be added but significantly increase the processing cost
Emitter Dopant

- N-type
  - N-type silicon has a higher surface quality than P-type silicon so it is placed at the front of the solar cell where most of the light is absorbed
  - Thus the top of the cell is the negative terminal and the rear of the cell is the positive terminal

Emitter Thickness

- < 1μm
  - A large fraction of the light is absorbed close to the front surface. By making the front layer very thin, a large fraction of the carriers generated by the incoming light are created within a diffusion length of the p-n junction

Doping Level of Emitter

- 100 Ω/□
  - The front junction is doped to a level sufficient to conduct away the generated electricity without excessive resistive losses
  - However, excessive doping levels reduces the material quality to the extent that carriers recombine before reaching the junction

Grid Pattern

- Fingers 20 – 200 μm wide spaced 1-5 mm apart
  - The resistivity of the silicon is too low to efficiently conduct all the current generated, so a low resistive metal is placed on the front surface to conduct away the current
  - The metal grid shades the cell from incoming light so there is a compromise between light collection and the resistance of the metal grid

Rear Contact

- The rear contact is much less important than the front contact since it is much further away from the junction and does not need to be transparent
  - The design of the rear contact becomes more important as cells become thinner and attempts are made to increase the overall efficiency

Design Trade-Offs: Efficiency and Cost

- Laboratory Cells near 25% efficiency
  - Commercially mass produced cells 13-14% efficiency
  - Why? Lower cost techniques and designs used for commercial products
### Laboratory Cell Features and Designs

- Lightly phosphorus diffused emitters to minimize recombination and avoid a dead layer at the cell surface
- Closely spaced metal lines to minimize lateral emitter resistive losses
- Very fine metal lines to minimize shading
- Polished surfaces to allow top metal patterning by photolithography
- Small area devices and good metal conductivities to minimize resistive losses in the metal grid
- Low metal contact areas and heavy doping at the surface of the silicon beneath the metal contact to minimize recombination
- Elaborate metallization schemes (Ti-Pd-Ag) which give low contact resistances
- Good rear surface passivation to reduce recombination
- Use of anti-reflection coatings, which can reduce surface reflection from 30% to well below 10%

### Cost Inhibitive Techniques

- Use of polished wafers
- Photolithography
- Small area devices
- Ti-Pd-Ag evaporated contacts
- Multiple layer antireflection coatings

### Commercially Viable Requirements

- Cheap Materials and Processes
- Simple Techniques and Processes
- High Throughput
- Large Area Devices
- Large Contact Areas
- Process Compatible with Textured Surfaces

### Massed Produced Fabrication

- Texturing of the surface to form pyramids
- Phosphorus diffusion of top surface
- Screen printing and firing of aluminum or Al-Ag paste to produce back surface field and rear contact
- Screen printing and firing of silver paste for front metal contact
- Edge junction isolation to destroy the conducting path between the front and rear contacts

### Review for Test #2 on Semiconductors

- Bond Model
- Band Model
- Doping
  - N-type
  - P-type
- Conductivity
- Resistivity
- Sheet Resistivity
- Energy Gaps
  - Indirect
  - Direct
- Carrier Concentrations
- Absorption of Light
- Generation
- Recombination
- Diffusion Current
- Drift Current
- PN Junction
  - Charge Distribution
  - Electric Field
  - Built-in Potential
- Photoelectric Effect
- Diode I-V Curve
- Photogenerated Current
- Active Region
- Collection Probability
- Quantum Efficiency
- Spectral Response
- Photovoltaic Effect
- Performance Factors
- Short Circuit Current
- Open Circuit Voltage
- Solar Cell I-V Curve
- Fill Factor
- Efficiency
- Resistance
  - Characteristic
  - Shunt
  - Series
- Design Trade-offs
\[ J = \sigma \, E \]

\[ \sigma = \frac{1}{\rho} \]

\[ \sigma = q \left( \mu_0 + \rho \mu_1 \right) - \left( \frac{2}{\eta} \left( \nabla \cdot \mathbf{E} \right) \right) \left( \nabla \cdot \mathbf{V} \right) \]

\[ J_E = q \frac{\partial \phi}{\partial t} \quad J_J = q \frac{\partial \phi}{\partial t} \]

\[ J_{electric} = \frac{J_E}{\mu_0} \quad J_{magnetic} = \frac{J_J}{\mu_0} \]

\[ \mathbf{E} = \frac{\partial \phi}{\partial \mathbf{r}} \quad \mathbf{E}_0 = \frac{\partial \phi_0}{\partial \mathbf{r}} \]

\[ V_e = \frac{\mu_0}{\eta} \left( \frac{N_p}{p} \right) \quad \eta = \frac{N_p}{p} \quad \frac{N_p}{p} \]

\[ q = \frac{\partial \phi}{\partial \mathbf{r}} \quad \frac{\partial \phi}{\partial \mathbf{r}} \]

\[ R_e = \frac{V_e}{I_e} \quad \frac{V_e}{I_e} \]

\[ FF = \frac{I_e}{V_e} \]

\[ \text{diffusion} \quad \text{drift} \]

\[ \mathbf{J}_E = \mathbf{J}_J \]

\[ \mathbf{E} = \nabla \phi \quad \mathbf{J} = \nabla \times \mathbf{E} \]

\[ kT \]