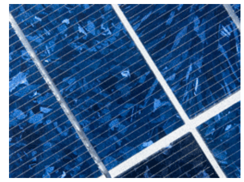
# EELE408 Photovoltaics
## Lecture 14: Solar Cell Design 2

Dr. Todd J. Kaiser
tjkaiser@ece.montana.edu

Department of Electrical and Computer Engineering
Montana State University - Bozeman

## Minimize Parasitic Resistive Losses

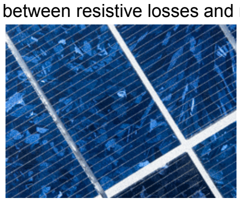
- Both shunt and series resistance losses decrease fill factor and efficiency
- Low shunt resistance is a processing defect rather than a design parameter
- Series resistance controlled by the top contact design and emitter resistance needs to be carefully designed





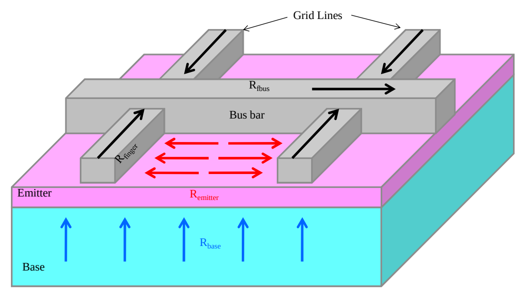
## Top Contacts

- 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





## Resistive components and current flows in a solar cell






## Base Resistance

- Generated current flows perpendicular to surface from the bulk, then laterally in the emitter
- Resistance is assumed isotropic
- Bulk Resistance:

$$R_b = \frac{\rho_b w}{A}$$

$\rho_b$ = Bulk Resistivity $(0.5\text{-}5\,\Omega\text{-cm})$

$w$ = Width of Bulk Region

$A$ = Area of Solar Cell



## Sheet Resistivity

$$R = \frac{\rho L}{A} = \frac{\rho L}{(t)(w)} = \frac{\rho}{t}\left(\frac{L}{w}\right)$$

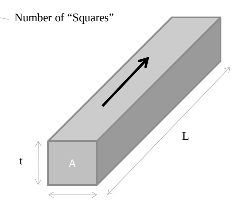
Number of "Squares"

$$\rho_s = \frac{\rho}{t} \qquad (Ohms/Square)$$

$\rho_s$ = Sheet Resistivity

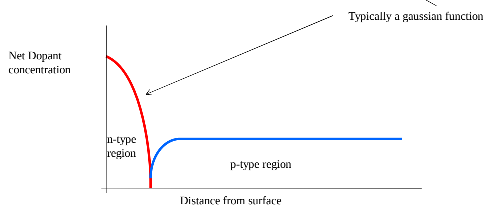
$\rho$ = Resistivity of the layer

t = Thickness of the layer



## Non-uniform Films

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



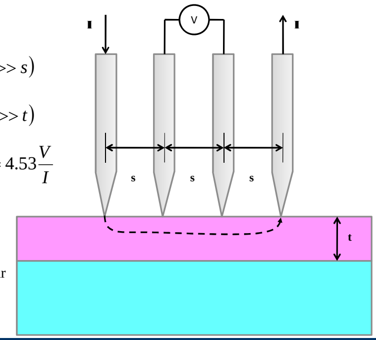

7

## 4-point Probe

$$\rho = 2\pi\ s\frac{V}{I} \qquad (t >> s)$$

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

$$\rho_s = \frac{\rho}{t} = \frac{\pi}{\ln 2}\frac{V}{I} = 4.53\frac{V}{I}$$




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

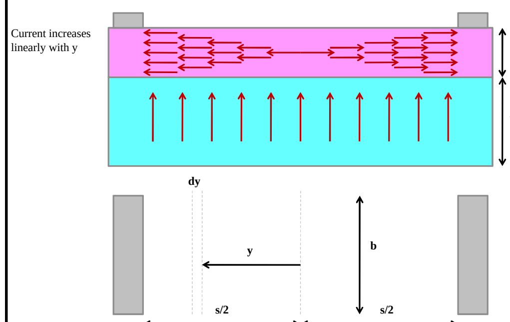
8

## 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

9

## Idealized Current Flow




10

## Calculation

$$dP_{loss} = I^2 dR$$

$$dR = \frac{\rho_s}{b}dy$$

$$I(y) = Jby$$

$$P_{loss} = \int_0^{\frac{s}{2}} (Jby)^2 \frac{\rho_s}{b}dy = \frac{J^2 b\rho_s s^3}{24}$$

$$J = 30\left(\frac{mA}{cm^2}\right)$$

$$b = 10(cm)$$

$$\rho_s = 100(\Omega / sq)$$

$$s = 2mm$$

$$P_{loss} = \frac{J^2 b\rho_s s^3}{24} = \frac{(.03)^2(10)(100)(.2)^3}{24} = 0.0003(W) = 0.3(mW)$$

11

## Fractional Power Loss

$$P_{GenMax} = J_{mp} b\frac{s}{2}V_{mp}$$

$$P_{\%lost} = \frac{P_{loss}}{P_{GenMax}} = \frac{\frac{J_{mp}{}^2 b\rho_s s^3}{24}}{J_{mp} b\frac{s}{2}V_{mp}} = \frac{\rho_s s^2 J_{mp}}{12V_{mp}}$$

For a lateral resistance loss of less than 4%

$$4\% = \frac{\rho_s s^2 J_{mp}}{12V_{mp}} = \frac{(40\Omega / sq)(s^2)(30mA/cm^2)}{12(0.45V)} \Rightarrow s \le .42cm$$

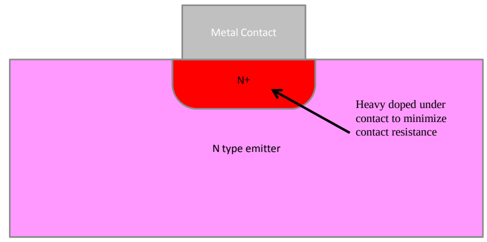
12

## 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



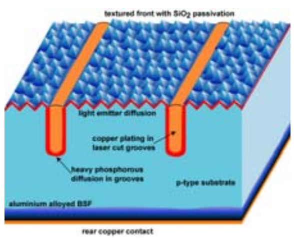
## Contact Doping






## Metal Grid Pattern

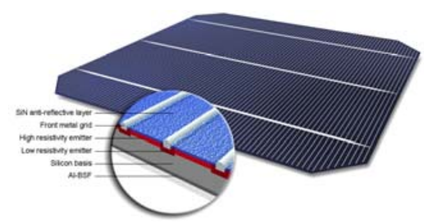
- Minimize losses associated with the top contact
  - Resistive losses in the emitter
  - Resistive losses in the metal top contact
  - Shading losses from the metal pattern






## 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

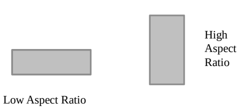





## Grid Resistance

- 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

$$\text{Aspect Ratio} = \frac{\text{height}}{\text{width}}$$



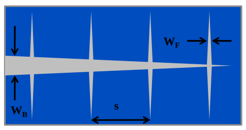



## Shading Losses

- 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
  - Determined by the width of the metal lines and their spacing
- 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 ($W_B$) 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 ($W_F$) and the smaller the finger spacing (s) the lower the loss






## Design Compromises

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



## Substrate Material

- **Silicon** dominates the market
  - Piggybacks the Integrate 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

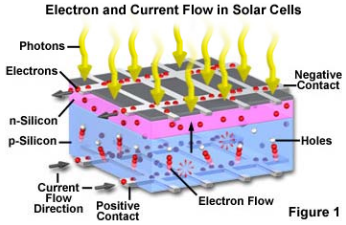
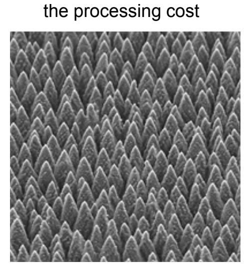


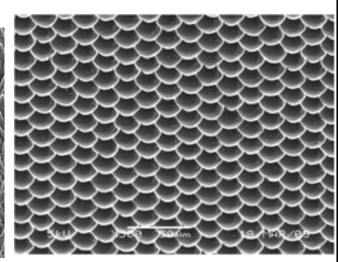

Figure 1



## Reflection Control

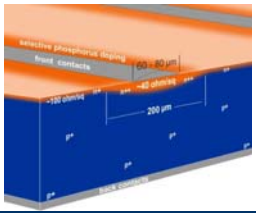
- Front surface typically **textured**
- Antireflection layers can be added but significantly increase the processing cost





## Emitter Dopant

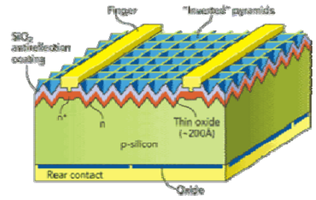
- **N-type**
- N-type silicon has a higher surface quality than P-type silicon so it is placed at the front of the solar cell where most of the light is absorbed
- Thus the top of the cell is the negative terminal and the rear of the cell is the positive terminal






## Emitter Thickness

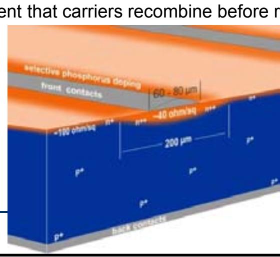
- **< 1µm**
- A large fraction of the light is absorbed close to the front surface. By making the front layer very thin, a large fraction of the carriers generated by the incoming light are created within a diffusion length of the p-n junction






## Doping Level of Emitter

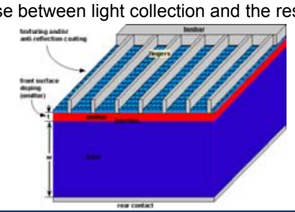
- **100 Ω/□**
- The front junction is doped to a level sufficient to conduct away the generated electricity without excessive resistive losses
- However, excessive doping levels reduces the material quality to the extent that carriers recombine before reaching the junction






## Grid Pattern

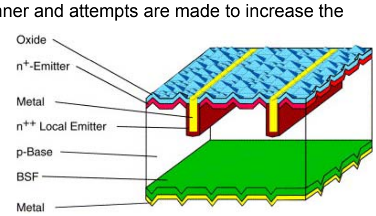
- **Fingers 20 – 200 µm wide spaced 1-5 mm apart**
- The resistivity of the silicon is too low to efficiently conduct the all the current generated, so a low resistive metal is placed on the front surface to conduct away the current
- The metal grid shades the cell from incoming light so there is a compromise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






## Rear Contact

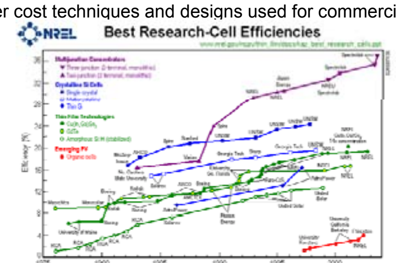
- The rear contact is much less important than the front contact since it is much further away from the junction and does not need to be transparent
- The design of the rear contact becomes more important as cells become thinner and attempts are made to increase the overall efficiency






## 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-Pa-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%

31

## Cost Inhibitive Techniques

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

32

## Commercially Viable Requirements

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

33

## 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

34

## 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

35

## Review for Test #2 on Semiconductors

- 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

36

## Equations

$$J = \sigma E$$

$$\sigma = \frac{1}{\rho}$$

$$\sigma = q(n\mu_n + p\mu_p)$$

$$W = W_n + W_p = \sqrt{\left(\frac{2\varepsilon N_A}{qN_D(N_A + N_D)}\right)(V_{bi} - V_A)} + \sqrt{\left(\frac{2\varepsilon N_D}{qN_A(N_A + N_D)}\right)(V_{bi} - V_A)}$$

$$= \sqrt{\left(\frac{2\varepsilon (N_A + N_D)}{qN_D N_A}\right)(V_{bi} - V_A)}$$

$$J_n = qD_n \frac{dn}{dx} \qquad J_p = -qD_p \frac{dp}{dx}$$

$$J_{drift} = J_{diffusion}$$

$$n = N_C e^{\frac{E_F - E_C}{kT}} = n_i e^{\frac{E_F - E_i}{kT}} \qquad E_F - E_i = kT \ln\left(\frac{n}{n_i}\right)$$

$$p = N_V e^{\frac{E_V - E_F}{kT}} = n_i e^{\frac{E_i - E_F}{kT}} \qquad E_F - E_i = -kT \ln\left(\frac{p}{n_i}\right)$$

$$J_p = qp\mu_p E \qquad J_n = qn\mu_n E$$

$$\frac{D_n}{\mu_n} = \frac{kT}{q} \qquad \frac{D_p}{\mu_p} = \frac{kT}{q}$$

$$I = I_0\left(e^{\frac{qV}{kT}} - 1\right) - I_L \qquad I_0 = A\left(\frac{qD_e n_i^2}{L_e N_A} + \frac{qD_h n_i^2}{L_h N_D}\right)$$

$$L_n = \sqrt{D_n \tau_n} \qquad L_p = \sqrt{D_p \tau_p}$$

$$I = I_0\left[\exp\left(\frac{q(V - IR_s)}{kT}\right) - 1\right] - I_L + \frac{V - IR_s}{R_{sh}}$$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} \qquad R_{ch} = \frac{V_{oc}}{I_{sc}} = \frac{V_{mp}}{I_{mp}} \qquad FF = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}}$$