Correlation of Cell Efficiency with Photoluminescence Images

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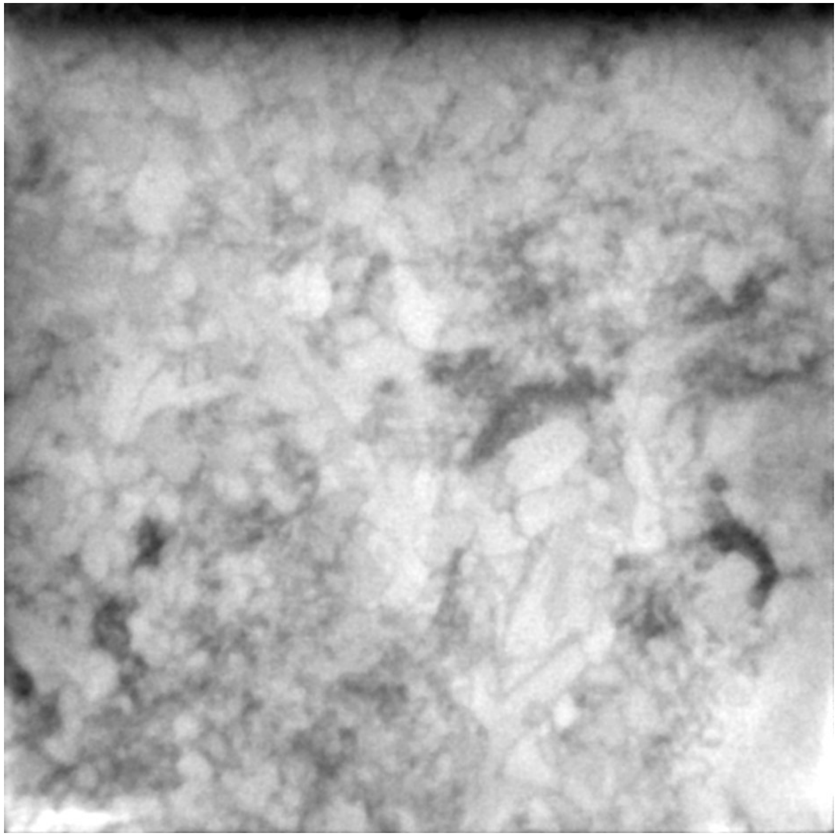
Silicon Photoluminescence

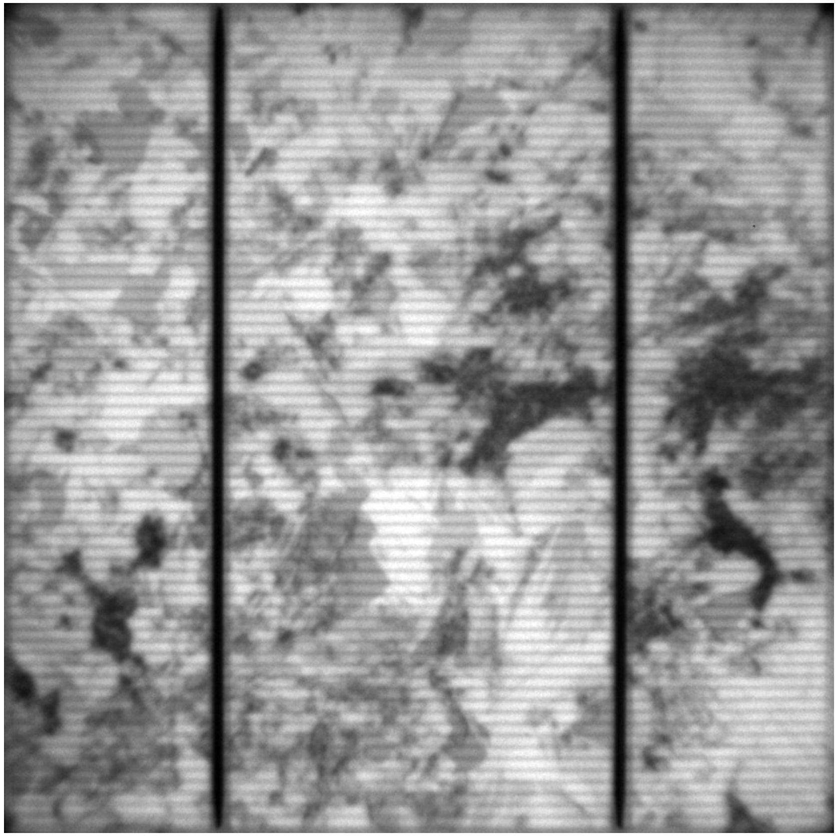
- **Photoluminescence**
  - Illumination with a wavelength shorter than the bandgap stimulates emission at the bandgap
- **Emission is related to minority carrier diffusion length**
  - Brighter emission implies higher conversion efficiency
- **Luminescence images show:**
  - Material quality
  - Dopant uniformity
  - Cracks
  - Crystal Defects

Photoluminescence Images

As-cut multi-crystalline wafer



Finished multi-crystalline cell



Photoluminescence

Advantages

- Applicable for in-process wafers or finished cells and assemblies
  - As-cut, textured, post-diffusion, post-ARC, metallized, finished cells
- No material contact required
  - No chance of breakage
  - Cell alignment not critical

Disadvantages

- Uniform illumination source required
- Trade-off between experiment time and image resolution
- Cell cooling for bright light sources required

Solar Cell Efficiency

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$$\eta \propto V_{OC} J_{sc} FF$$

- Voc is the open circuit voltage of the cell
  - Depends largely on the quality of the silicon
- Jsc is the short circuit current density of the cell
  - Depends on the design and processing of the cell and the quality of the silicon
- FF is the fill factor of the cell
  - Depends largely on the electrical properties of the finished cell

- Photoluminescence correlates with Voc and Jsc, but not FF.
- The product of Voc and Jsc can be used as a measure of material quality.

Features that affect the wafer quality

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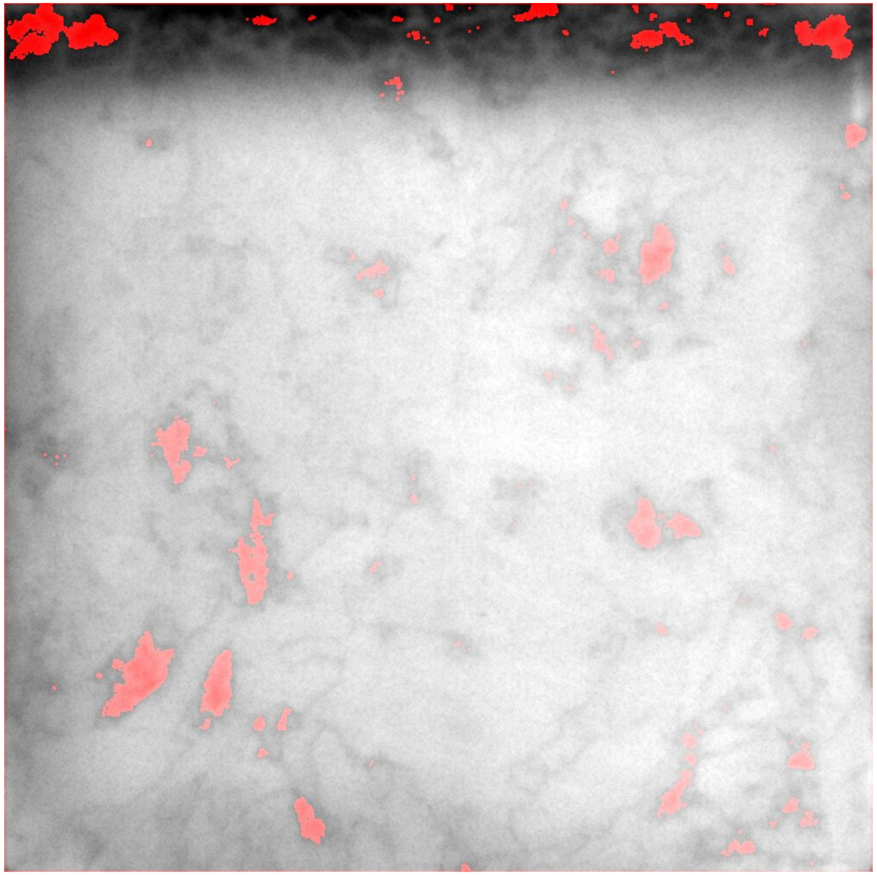
- Dislocation Clusters
  - Area where many crystal defects have aggregated during casting
  - Increase recombination and impede carrier flow
- Edge Impurities
  - Foreign atoms diffuse in from the walls of the crucible
  - Impurities reduce the carrier lifetime
  - Some gettering of impurities is possible during processing
- Grain Boundaries
  - Location where crystals of differing orientations meet
  - Attracts impurities and impedes carrier flow

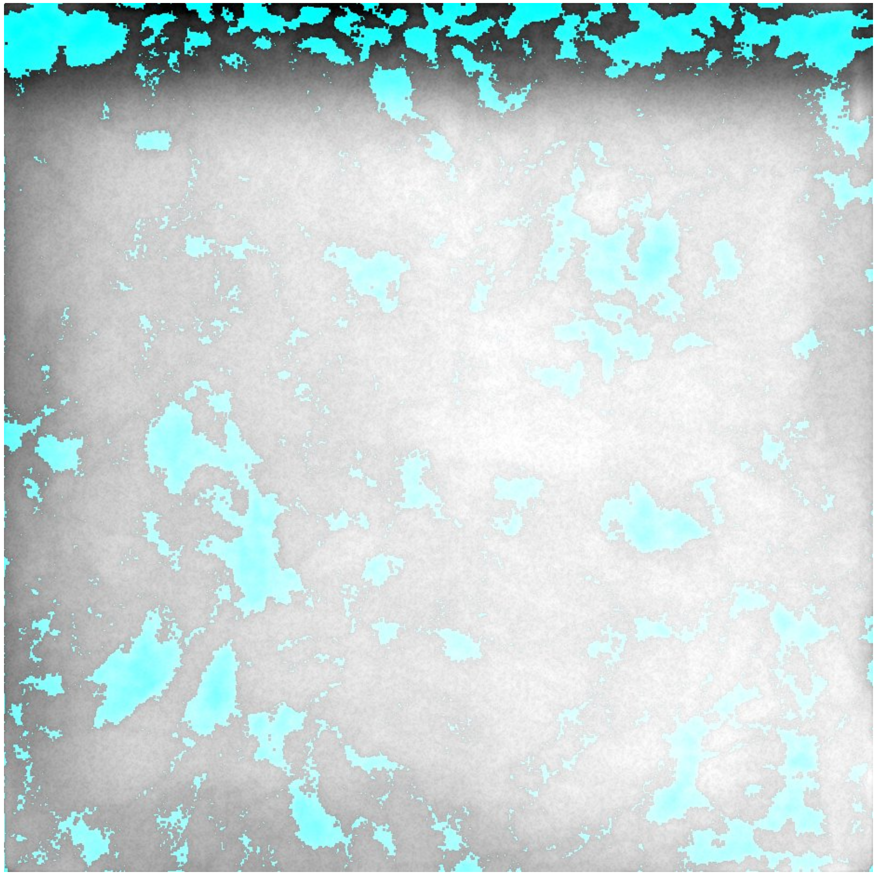
Dislocations

- **Appear as very dark patches in the PL image**
- **Need to eliminate intensity variations due to impurities and doping nonuniformity**
  - **Low stop filter**
- **A simple intensity level threshold is able to identify the dark patches**



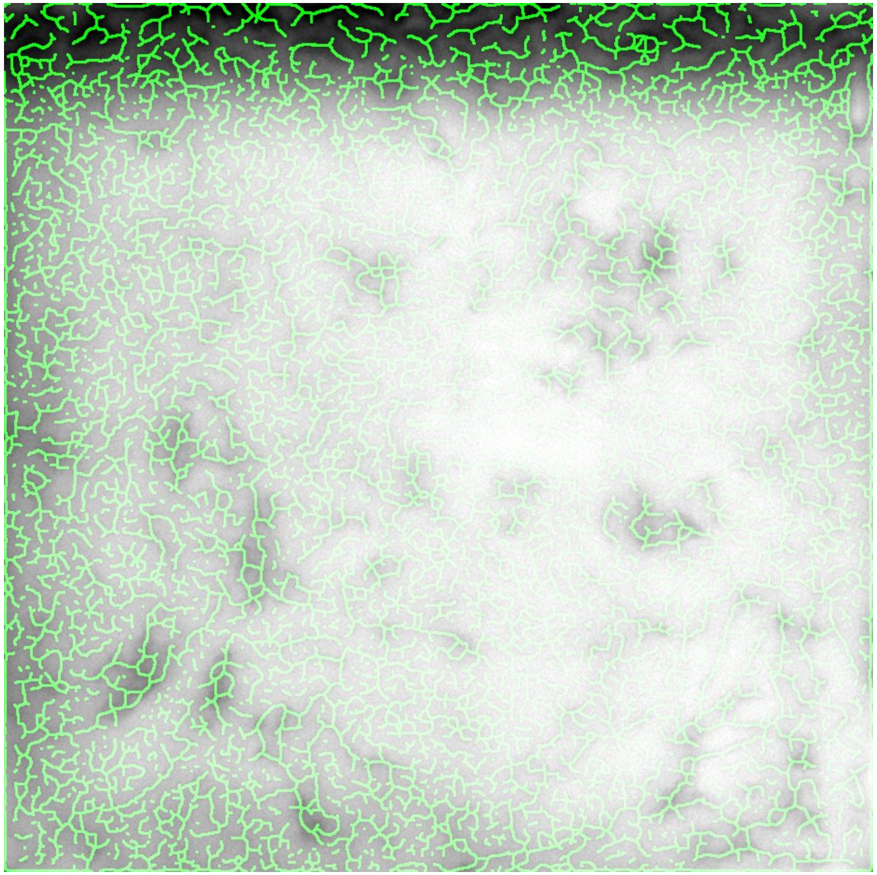
Other Defects

- **Choosing a second threshold level highlights the areas with reduced lifetime**



Grain Boundaries

- **Appear as narrow dark lines in the PL image**
  - **narrow bright lines in the edge impurity regions**
- **Comprise the high frequency information of the PL image**
- **Can be extracted from using a bandpass filter**



Edge Impurities

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- **Two distinguishing characteristics in the PL image**
  - Darker than rest of the wafer
  - Grain boundaries are brighter than the surrounding silicon
- **Use a combination of intensity threshold and histogram pattern to identify impurity regions**

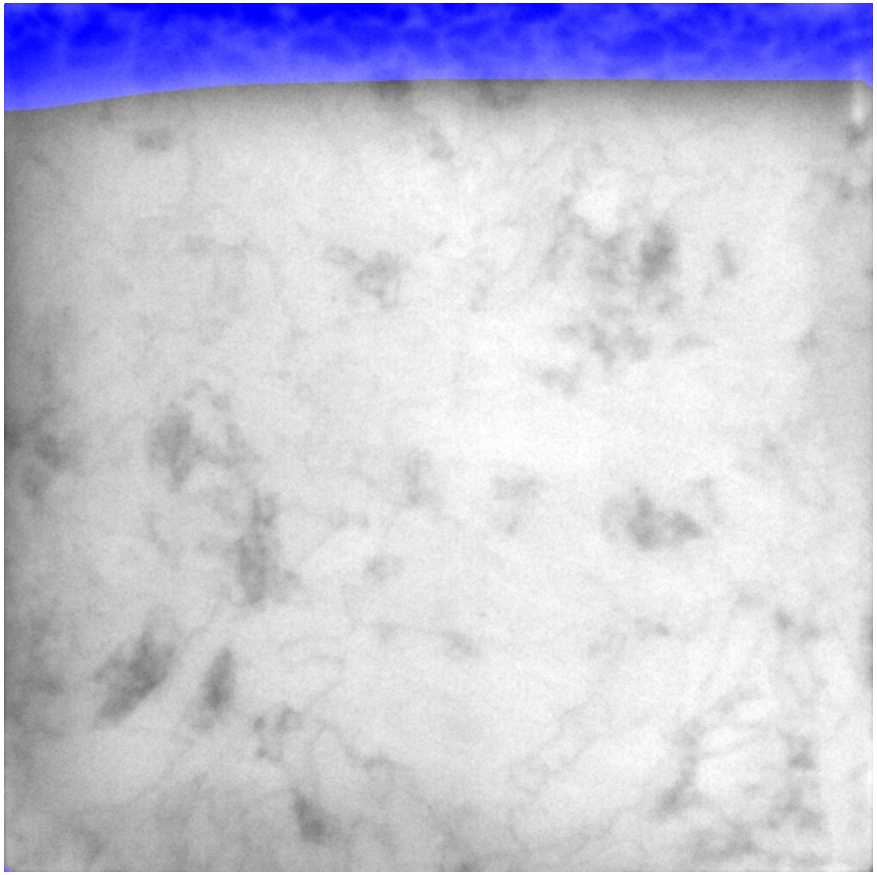
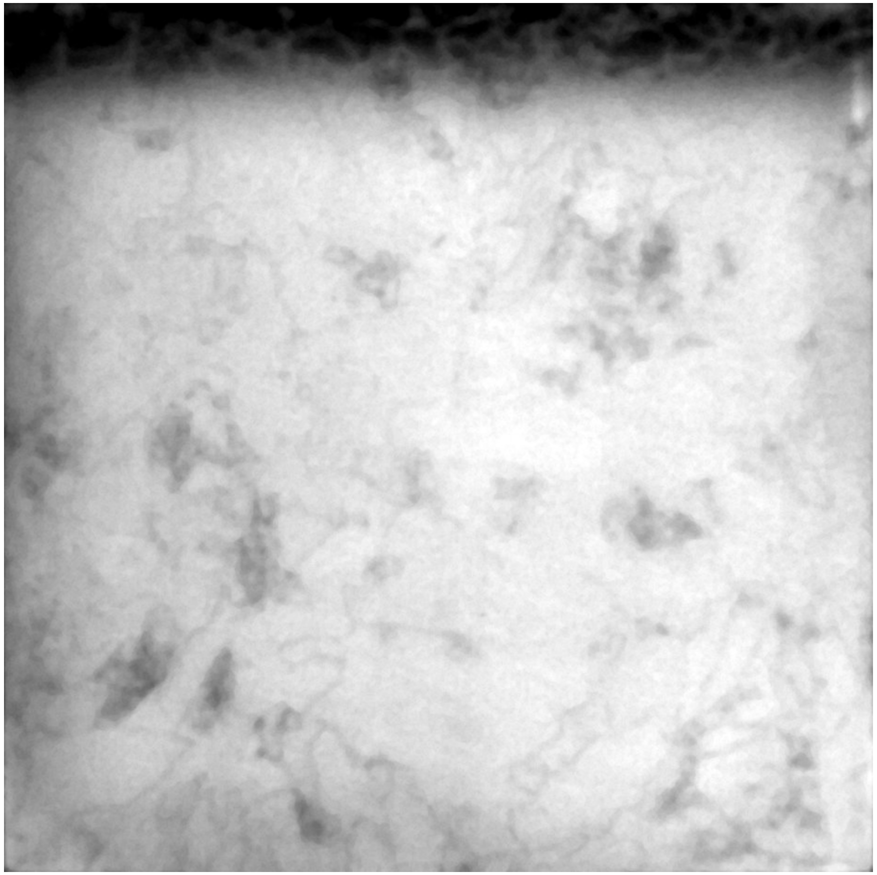


Image Statistics

- **Basic image statistics reveal much of the wafer quality**
  - Mean intensity
  - Intensity standard deviation
  - Image histogram
  - Map of the local standard deviation
- **The same statistics can be recalculated after excluding the edge impurity region**



Wafer Quality Prediction

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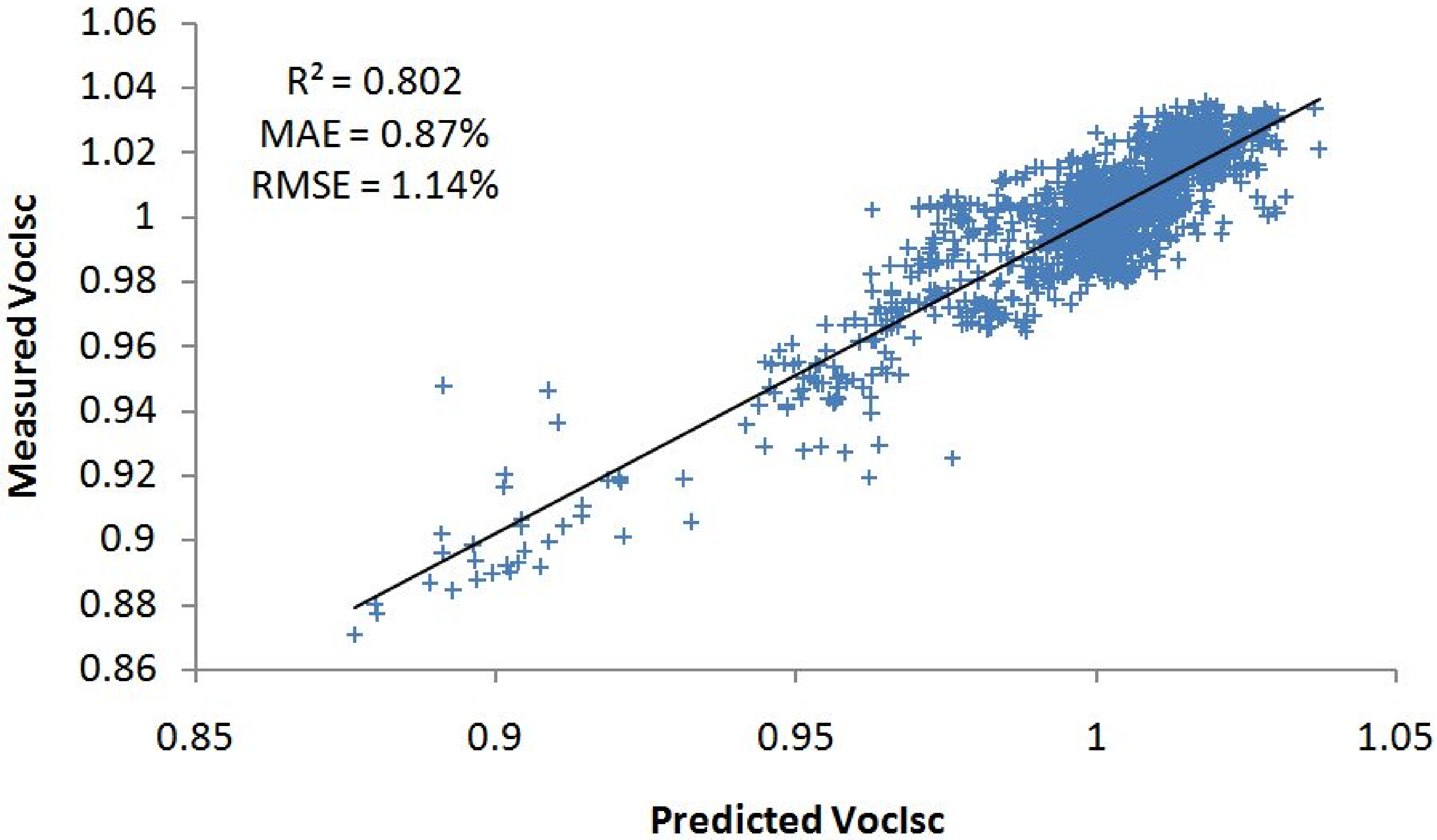
- A large training set of wafers is collected.
  - Each wafer is imaged by photoluminescence.
  - The thickness and resistance of each wafer is measured.
  - The wafer are processed into finished cells and the electrical properties are measured.
- A second test set of wafer is also collected and processed in the same manner as the training set
  - Alternately, the test set can be divided into smaller groups and internally cross-validated.
- A machine learning algorithm builds a model of the finished cell electrical properties based on the wafer metrics
  - The model can be process agnostic for general material quality.
  - For the highest accuracy, the model must be process specific.

Fit of a Data Set of ~1500 wafers



Coefficient of Determination R^2

$$R^2 \equiv 1 - \frac{\sum \left(y_i - f(x_i)\right)^2}{\sum (y_i - \bar{y})^2}$$

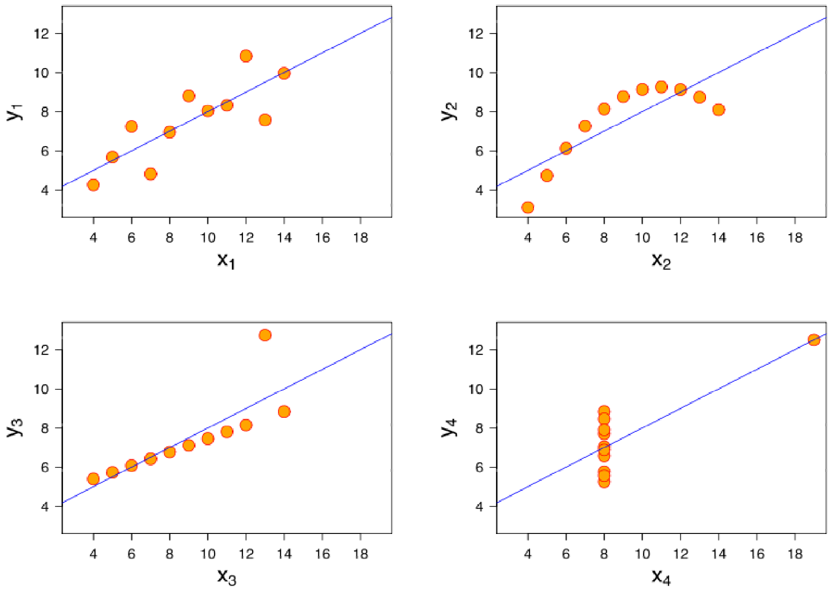
A measure used in statistical model analysis to assess how well a model explains and predicts future outcomes. It is indicative of the level of explained variability in the model. The coefficient, also commonly known as R-square, is used as a guideline to measure the accuracy of the model.

In general, the higher the R^2 the better the predictability of the model.

However…

Problems with R-square

- These four charts have the same R^2 value (0.66)
- Long tails have a large impact on R^2 value.
- Outliers can have a disproportionate effect on R^2.



http://en.wikipedia.org/w/index.php?title=Anscombe%27s_quartet&oldid=465616431

Mean Absolute Error

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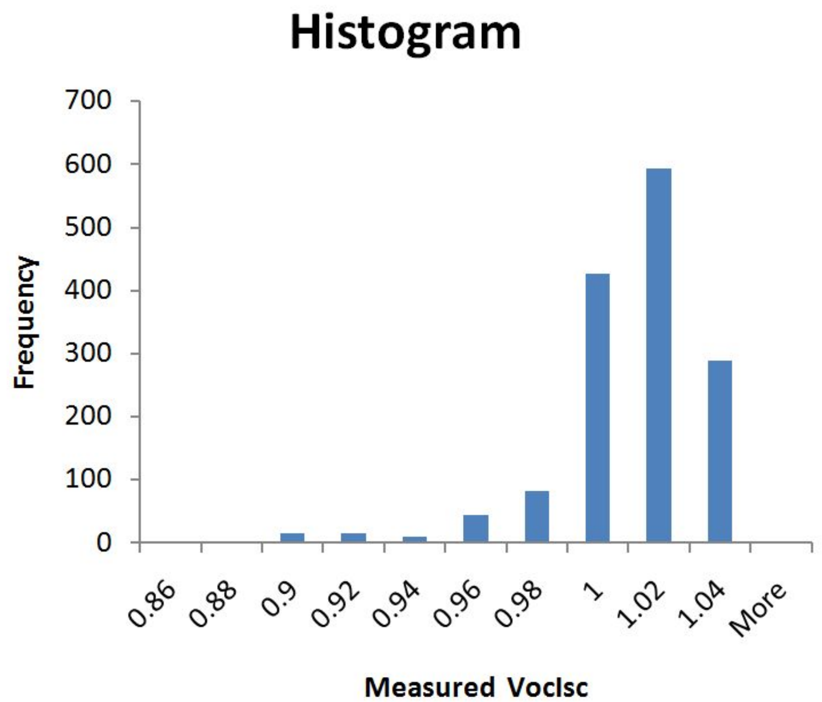
$$MAE = \frac{1}{n}\sum \left| f(x_i) - y_i \right|$$

$$RMSE = \sqrt{\frac{1}{n}\sum \left(f(x_i) - y_i \right)^2}$$

- The **mean absolute error (MAE)** is a quantity used to measure how close forecasts or predictions are to the eventual outcomes.
- The root mean square error (RMSE) is a similar measure of the differences between the predicted and measured values.
- They are unaffected by data with a long tail.

Distribution of Wafer Quality



- **Typical multi-crystalline silicon production yields a skewed distribution with long tail of lower quality material.**
- **Removing low quality material before processing will shift the average efficiency higher and improve the line yield.**

Conclusions

- **Photoluminescence images can be used as a predictor of wafer quality.**
- **Low quality wafers can be rejected at the as-cut stage, before being processed into cells.**
  - **Saves processing costs**
  - **Material at the as-cut stage can be recycled.**
- **Good quality wafers can be segregated into quality or other bins**
  - **Leads to better factory output prediction**
  - **Different bins can be processed through different lines for higher efficiency**

Thank you for your time.

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