Advanced in-line characterization and sorting of crystalline silicon photovoltaic wafers

Workshop on Test Methods for Silicon Feedstock Materials, Bricks and Wafers, SEMI PV Materials Standards Committee
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Outline

- In-line characterization and sorting
- In-line measurement technologies
- Photoluminescence combined with lifetime calibration by MW-PCD technique
- Quasi-steady-state (QSS) MW-PCD technique
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<td>Thickness</td>
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Each module can be integrated into Semilab wafer sorter equipment
Many other tools under development
Sorter purpose:

- Eliminating damaged wafers from further process
- Sorting out potentially weak wafers (microcrack) which could break in further process steps
- Eliminating high thickness variation wafers (TTV, saw mark)
- Sorting out low lifetime wafers
- Sorting based on resistivity value

Application area:

- Outgoing wafer inspection for wafer manufacturers
- Incoming wafer inspection for solar cell manufacturers

An inspection line concept:
µ-PCD lifetime linescan measurement

- Periodic laser pulses excite the material generating free charge carriers, which recombine at recombination centers.
- This transient process is monitored by recording the reflected microwave power as a function of time.
- Since the MW reflection depends on the conductivity, the conductivity transient can be measured and evaluated.
- The transient curve is fitted and the extracted time constant is the lifetime, which characterizes the material quality.
• Conveyor belt moves during measurement
• Data can be recorded in 1 and 3 lines

Tools configuration

1 line
3 lines

1
3

1
3

1
3

1
3

1
3


Fast in-line lifetime mapping

- Fast in-line Lifetime Mapping (Fast-ILM) tool is using a novel way of transient \( \mu \)-PCD method
- It enables fast & full wafer data acquisition and lifetime evaluation.
- Fully compliant with requirements for in-line wafer characterization
- Acquisition time: < 1 s
- Resolution: 90 x 90 points
P/N tester measurement is based on the SPV (Surface Photovoltage) technique.

Resistivity measurement uses Eddy current technique.

Resistivity calculation needs thickness information.

Thickness is measured independently by double-sided distance measurement.

Distance measurement can be carried out in two ways:
- By capacitive probe
- By optical probe

Using the optical probe configuration saw marks can be also detected due to its fine lateral resolution.
2D geometry measurement

- By using back- and top-light – the contrast is measured.
- The following parameters are determined:
  - Side lengths
  - Diagonals
  - Angles
**Edge Chipping, Surface Contamination**

Two main inspection categories:

- Breakage, edge and chipping inspection (40µm pixel resolution, length, width, area and counting)
- Contamination (stain) inspection (80µm pixel resolution, length, width, area and counting)
- Grain distribution
- Sori

The Wafer Surface Station is performing an automatic measurement of chipping, contamination and edge defects. The system is using a complex illumination with two line scan cameras on each side and a PCs for image collection, processing and for user & process interface software. The Surface master profile software coordinates the measurements and sends the accumulated results for classification.
Imaging description

- A wafer is transported into the sensor unit.
- The wafer triggers a signal via a light barrier causing an image capture.
- The halogen lamp in the illumination unit illuminates the wafer.
- The camera captures an image. The wafer images are transmitted to the PC for image processing.
- The image processing software detects defects and classifies them according to the configuration.
- Individual inspection parameter sets can be configured and loaded for each type of wafer.
Microcrack inspection

Application:

- Microcrack inspection system
- Incoming wafer inspection and sorting

MCI System detects:

- Microcracks
  ![Microcracks](image1.png)

- Material inclusions
  ![Material inclusions](image2.png)

- Holes
  ![Holes](image3.png)
Photoluminescence measurement

• Applicable for wafers at any processing stage from as cut wafers to finished cells.

• High resolution images allow detection of
  • defects around grain boundaries, dislocations.
  • low lifetime areas on edge and corner wafers

• Wafer classification is based on statistics of full lifetime map.

• Correlation of PL and lifetime is carried out by calibration with simultaneous μ-PCD measurements.
Photoluminescence measurement principle

- Excitation of charge carriers is carried out with high intensity illumination
- Charge carriers recombine
- The radiative recombination is proportional with the product of electron and hole concentrations, and excess carrier concentration is proportional to the effective lifetime, thus rate of **radiative recombination is proportional to effective lifetime**
- During radiative recombination, a photon is emitted, which can be detected by an IR camera
- PL intensity is inversely proportional to defect density and impurity concentration
- Good imaging technique, but gives only relative results within the wafer
- To get quantitative results or wafer to wafer comparison, calibration is needed to absolute methods such as lifetime measurements
Comparing to $\mu$PCD map result

Photoluminescence:
156 mm mono-like wafer results
PL and \( \mu \)-PCD sensitivity regarding surface quality

- PL signal is sensitive to surface quality
- Comparison of as-cut and etched PL line-scans show high variation in PL signal
- MW-PCD line-scans on the same wafers show stable measured lifetime
- MW-PCD is a stable tool for monitoring as-cut wafers and can be used for calibration of PL

*accepted for the 27th European Photovoltaic Solar Energy Conference, 24-28 Sept 2012
Comparison of photoluminescence and MW-PCD

- Photoluminescence (PL) signal and MW-PCD lifetime shows excellent correlation on as-cut wafers
- Comparison of line-scan of PL images and MW-PCD lifetime map demonstrates that MW-PCD is valid tool for PL calibration
- Advantage: MW-PCD lifetime is much less sensitive on surface quality than PL*

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In conventional steady-state and quasi-steady-state methods the lifetime is calculated from two measured quantities; 1) the magnitude of photoconductivity $\Delta \sigma$, e.g. by Eddy current and 2) the generation rate $G$, e.g. by measuring illumination intensity and 3) knowing the carrier mobilities $(\mu_n + \mu_p)$.

steady-state equation: \[ \tau_{\text{eff}} (\Delta n) = \Delta n / G \ldots \quad 1. \]

The **QSS-µ-PCD** is using another approach:
- Basore and Hansen (1990) derived equations describing the excess carrier decay after small perturbation laser pulse excitation on background of steady-state light bias.
- Therefore in **QSS-µ-PCD**, $\tau_{\text{eff}}$ is obtained directly from the time decay of photoconductivity $\Delta \sigma$ measured in linear microwave reflectance range after short laser pulse.
- The QSS generation rate $G$ is pre-calibrated. Therefore, the steady-state equation can be reversed giving the injection level, $\Delta n$.

reverse procedure: \[ \Delta n = G \cdot \tau_{\text{eff,ss}} \ldots \quad 2. \]

Equation 2 relates $\Delta n$ and $\tau_{\text{eff}}$ and defines the injection level. There is:
- no need for absolute $\Delta \sigma$ calibration
- no need to know $(\mu_n + \mu_p)$
- no need to precisely know $G$ in laser pulse

➢ **Direct measurement & mapping of QSS-µ-PCD lifetime.**
QSS-µ-PCD PRINCIPLE
(QUASI ≡ ALMOST)

small perturbation method

Life time is measured at different steady-state generation values G, which are varied in time intervals larger than lifetime. µ-PCD laser power is small compared to G (small perturbation). Each \( \tau_1 \), \( \tau_2 \) ... corresponds to well-defined injection levels \( \Delta n_1 \), \( \Delta n_2 \) ...

Note: Steady illumination from wafer back side can also be used when wafer support and reflector plate are transparent to light.
• Steady-state lifetime $\tau_{\text{eff.ss}}$ is obtained from decay lifetime $\tau_{\text{eff.d}}$ by integration over light intensity (procedure of Schuurman et. al 1997)
• No wafer parameters are required
• Results are compared with Sinton’s QSSPC*

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Thank you!

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