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Summary of the Second Working Group Meeting on the Minority Carrier Diffusion Length/ Lifetime Measurement

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Minority carrier diffusion length/recombination lifetime (L or τ) is now seriously considered by the photovoltaic (PV) industry to be a parameter that can be used to monitor the material quality as well as to develop cell fabrication processes suitable for yielding higher cell efficiencies. In fact, many commercial solar cell manufacturers already use this approach for process control. Several techniques, based on RF-PCD, LM-PCD, and SPV, are currently used for the measurement of L or τ. The measurement of L (or τ) can also be applied in the IC industry for monitoring the quality of the as-grown material and for monitoring the cleanliness of furnaces. However, because the bulk L or τ is not critical to the performance of IC devices such as memories or microprocessors, the measurement of L or τ is not used for the IC device quality control. Instead, it is the generation lifetime at the wafer surface region that is monitored.

Although the general methodologies for measuring L (or τ) are well established, the physics for interpreting the measured data is not well understood. For example, it is now known that injection level, light intensity, and material/device nonuniformity can influence the measured values. In view of the importance of this measurement, it is necessary to improve the current methods and develop a new understanding so that the data can be meaningfully interpreted. The purpose of the working group meetings is to develop L (or τ) measurement procedure(s) that yield meaningful results which can help PV engineers or scientists to evaluate material quality, predict the cell performance, and to arrive at optimal cell processing recipes. However, to have faith in the measurement, it is necessary to understand how the measured entity is influenced by the measurement conditions. For example, because today's Si has few deep-level impurities, surfaces play an increasingly important role during lifetime measurements.

The First Working Group Meeting (1-WGM), held in January, 1993, served two purposes. The group examined the usefulness of various L (or τ) measurement techniques, and initiated data collection that would determine correlations among various measurement methods, and among similar measurements performed at different laboratories. This led to our first round robin testing (1-RRT). The results of round robin tests took a long time and some measurements could not be carried out under appropriate operating conditions.

The Second Working Group Meeting (2-WGM) on the measurement of the Minority Carrier Diffusion Length/Lifetime (L or τ) was held on January 17-19, 1996, in Scottsdale, AZ. The purpose of the meeting was to provide a forum for discussing new understanding of the measurment of L (or τ) in silicon wafers and devices, and the application of these measurements to device processing and process control in both photovoltaic and non-photovoltaic fields. The specific objective of this meeting was to discuss the following topics:

- The results of the 1-RRT, performed by different facilities equiped with L or τ measurement capabilities, to compare inter-laboratory values of L or τ
- The recent advances in the measurement techniques and data interpretation
- The recommendations for the second round robin tests (2-RRT)

The 2-WGM was attended by 34 researchers representing PV and microelectronics industries, universities, and other research organizations. These include: ASE Americas, Solarex, EBARA Solar, Astropower, SEH America, Siltec Silicon, MEMC, Motorola, ASU, GIT, MIT, University of California at Berkeley, University of South Florida, North Carolina State University, Duke, NREL and Sandia. Several equipment manufacturers also participated, including Semiconductor Diagonostics, Semilab (Hungary), GeMeTec (Germany), Biorad, and Sinton Consulting. This meeting provided an opportunity to clarify the measurement conditions that must be observed and specified for a given lifetime measurement method. The following is a summary of various issues that the meeting attendees dealt with.

• There was fair agreement among the values of L or τ obtained by various methods used in 1-RRT. Nevertheless, there was also a considerable scatter in the data even for similar measurement methods, e.g. between rf PCD and LM-PCD. This scatter could be reconciled by the fact that operating conditions for various techniques differ. Because the lifetime depends on parameters such as carrier injection level, temperature, and surface recombination velocity (and possibly on other parameters as well), the scatter could be attributed to different measurement conditions. Therefore, it is very important to specify measurement conditions and address the following questions: Is the Si wafer bare, oxidized, or covered with a passivating liquid (HF, iodine/methanol)? What injection level is used during the measurement? On what part of a decay curve for PCD measurements is the lifetime determined? Is the SPV measurement made under constant voltage or constant photon flux conditions? Stating only "the lifetime was measured with LM-PCD" or "the diffusion length was measured with SPV" is insufficient.

• The workshop concluded that the following relations apply as "rules of thumb" in general in the measurement of L or τ for a wafer of thickness W, and surface recombination velocity S:

— $L_d\,(\mu m) = 50\,[\tau\,(\mu s)]^{1/2}$

— $\tau_{diff}\,(\mu s) = 10\,[W\,(\mu m)/500]^2$ = lower limit for s $\rightarrow\infty$

— $\tau = W/2S$, for a wafer controlled by surface recombination
$= 10\mu s$, for $W = 500\mu m$ and $S = 2.5 \times 10^5$ cm/s. Hence, the expression is valid for $S \geq 10^4$ cm/s

• The round robin review concluded that the agreement on a numerical basis is less significant than accurate measurement of the appropriate material metric. Thus, the goal is correlation of the measured lifetime/diffusion length values, measured at various stages of cell processing, with the performance of the finished cell. The key issues are:
— measurement conditions vs cell operating conditions
— variation in the material heterogeneity
— variation in the material upgradability
Solving these issues requires either standardizing materials to a single specification or different measurement specifications for each source material.

• The group unanimously agreed that the desired measurement range is τ = 1-10 µs to make 18% solar cells on the current substrate thicknesses.

• The group agreed to perform a second, interactive round robin with the goal of developing a meaningful indicator of material quality.

The 2-RRT project will have the following content:

1. A variety of material types and sources were selected by the group.These samples will be sent to the measurement team as each becomes available. Deadlines of 2/10/96 for delivery of the first samples and 3/1/96 for reporting results to NREL were set. An

interactive review and remeasurement process should produce consensus measurement results and procedures by 6/1/96.

2. Reference high quality samples will be measured for calibration purposes. Values of the diffusion coefficients for electrons and holes, D(e) and D(h) respectively, will be determined from L and τ.

3. Standard process intervals will be used to select samples for each material source. There was some agreement that the measurement after the first diffusion would be the earliest indicator.

4. Variation of background light bias will be employed to remove trapping effects and simulate operating conditions. Measurements will be made as a function of light bias flux. The maximum power point injection level was determined to be an appropriate measurement condition.

5. The variation of measurement spot size will be included to determine its influence for inhomogeneous materials for each source.

6. An accuracy of 20% will be required. The reproducibility standard deviation for each laboratory will also be reported.

7. PCD measurements will report decay curves for 2 decades of injection level.

8. IQE measurements will include junction removal and measurements to separate L and S.

- The group often addressed the following questions:

— Is the lifetime a good predictor of solar cell performance? No clear answer emerged for this question. In fact, at least one solar cell company does not measure lifetime.

— What does lifetime mean on a nonuniform material like poly-Si that has considerable variation over the wafer? There were comments that lifetimes measured on incoming wafers have little correlation with cell efficiencies. This tends to negate the efficacy of lifetime measurements. An "average" value of L or τ, obtained by large-area measurement may not be meaningful in predicting solar cell performance. Such a value may selectively emphasize values from the regions corresponding to low or high values of L or τ. It was agreed that until further understanding is acquired, spatial mapping of L or τ will be done on non-uniform wafers.

The general findings at the workshop are the following:

A. Commercial lifetime measuring equipment is being sold more than ever in the semiconductor history.

B. Lifetime is one of the few parameters giving information on the low defect densities consistent with today's solar cells and ICs. No other technique can detect the effects of defect densities as low as 10^{10}-10^{11} cm^{-3} for ICs and 10^{11} -10^{12} cm^{-3} for solar cells in a simple measurement before the device is completely fabricated. Furthermore, the availability of commercial equipment makes these measurements relatively simple.

C. For both the solar cell and IC community, L or τ is a measure of growth, process and equipment cleanliness. It is important to make sure that the measurement conditions are well understood and stated, i.e. injection level, surface condition, etc. L or τ should not be used as a final device predictor; instead, it should be used to follow the growth and process cleanliness.

D. A good communication between the groups – those making the wafers and those making the measurements – should be established for the 2-RRT. Otherwise, the only difference from the 1-RRT will be more measurement data.