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Short communication

Fast, high resolution, inline contactless electrical semiconductor characterization for photovoltaic applications by microwave detected photoconductivity

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ABSTRACT

The state-of-the art lifetime measurement technique MDP (microwave detected photoconductivity) is presented with its latest developments in sensitivity, measurement speed and data simulation. Several applications and examples in the field of inline material characterization, defect recognition and real time statistical process control in silicon bricks and wafers are presented, demonstrating the practical use of MDP measurements and of the data obtained by it. The measured lifetime itself combined with its spatial distribution and the measured steady state photoconductivity enable a good correlation to the cell efficiency. Furthermore, the paper presents a detailed summary of the properties of steady state and non-steady state microwave based minority carrier lifetime measurement techniques to complete this extensive study.

1. Introduction

In addition to processing techniques, the properties of electronic devices, such as solar cells, strongly depend on the inherent electrical properties of the material. For example, the simple diode equation for a solar cell requires electrical properties such as the minority carrier lifetime as starting parameters. Good correlations between the open circuit voltage and short circuit current with the minority carrier lifetime of solar cells were demonstrated experimentally in a variety of approaches [1]. It is obvious that measurements of the carrier lifetime are most useful if they are performed as early as possible in the production chain, starting with mono-crystalline or multi-crystalline bricks and not passivated wafers.

An important factor is the measurement strategy for the carrier lifetime. For inline applications, these measurements must be contactless with high speed and high spatial resolution. Furthermore, the lifetime data must quantitatively reflect the bulk recombination lifetime, to represent the material quality and not only the surface quality.

Among the different measurement strategies for the minority carrier lifetime, microwave detected photoconductivity (MDP) meets all requirements. It uses a steady state measurement regime, but avoids the resolution problems inherent in other steady state measurement techniques. It is much less influenced by surface recombination than, e.g., μPCD (microwave detected photoconductive decay) [2,3]. In contrast to photoluminescence techniques, MDP data are inherently quantitative.

In this paper, high resolution lifetime maps together with contactless resistivity measurements of bricks are presented, which were obtained in less than a minute for each brick side. Examples of the information that can be gained by these measurements are given, such as the precise automatic cutting criteria or the over compensated n-type areas in the brick. The data provide instantaneous information for statistical process control and the optimization of processing steps, such as furnace operation.

MDP wafer measurement tools provide full wafer maps on as grown multi-crystalline wafers with a resolution of better than 2 mm in less than 1 s, which was presented in a previous paper [4]. This technique is particularly useful for standard process control and the prediction of expected cell efficiencies. Surface recombination is a major concern when performing lifetime measurements on wafers [5]. However, in this paper, the prediction of cell efficiencies based on lifetime values in combination with an evaluation of the spatial lifetime distribution is presented.

2. Methods

The standard materials under investigation are multi- and mono-crystalline silicon bricks and unpassivated wafers for photovoltaic production with resistivities of 0.5–3 Ω cm.

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The MDP method applied here measures the photoconductivity during and after a rectangular laser pulse by microwave (9–10 GHz) absorption via a resonant microwave cavity [6]. The sample is located just outside the microwave cavity and its complex dielectric constant influences the resonant frequency and the loss properties of the cavity. This setup yields a superior detection sensitivity compared to conventional setups. The high sensitivity enables injection dependent measurements over 8 orders of magnitude, e.g., in low injection to investigate trapping [7]. Furthermore, very thin layers (<10 μm) or metalized solar cells can also be measured [8]. Another consequence is that a very high measurement speed is possible because it is not necessary to average over many measurements to gain a good signal to noise ratio. Using more than one laser and cavity additionally increases the measurement speed.

Carrier excitation is performed by laser diodes at 980 nm with a photon energy slightly exceeding the band gap of silicon. The laser pulse duration can be varied from 0.2 μs to several milliseconds. For example, for brick measurements, long excitation pulses are applied to obtain a large influence from the bulk. If information about the surface is wanted, short pulses can be applied. Such short pulses cause a high carrier concentration close to the surface, which results in a strong influence of surface recombination [2]. However, the goal is generally to obtain a successful correlation between the measured lifetime values for the material in an early production step and the properties of the final product, e.g., the cell efficiency. This correlation strictly implies that the lifetime should be measured under the conditions of the final product under normal operation. For solar cells, the lifetime should be measured under the steady state conditions as created by the sun in the solar cell. Hence, a laser pulse of moderate intensity is applied for a sufficiently long time to allow the sample to reach a steady state. After switching off the light, the photoconductivity immediately exhibits the characteristic lifetime transient (Fig. 1a).

Another well-known approach is the μPCD technique, where the photoconductivity as initiated by a very high intensity laser pulse (13–16 W) of typically 200 ns is detected via microwave reflection measurements. This detection method usually causes relatively high microwave signals, which are easily detected. However, the laser pulse causes a condition in the sample that is far from steady state. Hence, the data are obscured by carrier diffusion, trap filling, carrier mobility effects, and recombination effects at various carrier concentrations. All of these effects together give rise to the surprising effect that the signal still increases after the light is switch off, as shown in Fig. 1b.

A further widely used method is the quasi steady state photoconductivity (QSSPC). This method is especially suited for injection dependent measurements and brick measurements because, it has a much higher penetration depth than the two methods mentioned above. However, the QSSPC method is limited by resolution due to the excitation by a flash lamp, which is a considerable drawback, especially for multi-crystalline and mono-like silicon characterization.

A completely different approach is used in photoluminescence methods. Instead of measuring the photoconductivity as in the methods mentioned before, the photoluminescence intensity is measured. The key advantage of the optical methods is the high spatial resolution combined with a high measurement speed. Many attempts were made to observe correlations between the carrier lifetime values as obtained by electrical characterization and photoluminescence imaging techniques [9–12]. However, for silicon as an indirect semiconductor, luminescence is a second order effect. The optical lifetime results depend on the doping and sample thickness. A calibration of the data by electrical methods such as QSSPC, μPCD or MDP [13] is necessary. However, for this calibration a single spot on the sample or even an average over a larger area are not really sufficient. The influence of material inhomogeneities such as doping variation, different defect and recombination center concentrations and differences between grains and grain boundaries in multi- or mono-crystalline silicon is significant. One must be very careful when taking luminescence data as a quantitative measure for the recombination lifetime of the excess carrier concentration in the conduction band. For a reliable calibration an entire lifetime map obtained by microwave-based techniques is necessary [14].

In Table 1, the most important properties of the different lifetime measurement approaches are summarized and compared.

For the production of semiconductor crystals, the control of segregation effects is a major concern and calls for reliable resistivity measurements as an integral part of the MDP equipment with no degradation of the overall system performance, in particular, the measurement speed. Eddy current-based sensors are used. However, with these sensors the measured effect strongly depends on the distance from the sensor to the sample surface, in particular, the brick surface. Any mechanical contact of the sensor with the surface is unacceptable. Therefore, the eddy sensor comprises a high precision distance sensor as an integral part, and the system uses a combined distance and resistivity calibration matrix. This technique altogether results in an excellent maintenance free, long term stability of the system. The typical repeatability is better than 3%

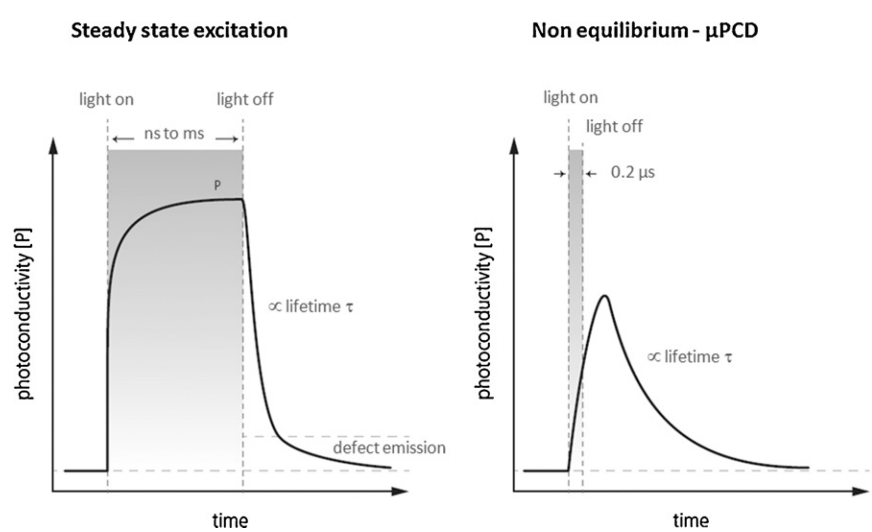

Fig. 1. Comparison of a typical steady state (MDP) and non-equilibrium (μPCD) measurement signal.