Solar Energy Materials and Solar Cells 185 (2018) 66–74

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Lock-in thermography with depth resolution on silicon solar cells

O. Breitenstein[a,*], H. Straube[b], K. Iwig[c]

[a] *Max Planck Institute of Microstructure Physics, Halle, Germany*
[b] *Jenoptik Optical Systems GmbH, Jena, Germany*
[c] *Dekra, Halle, Germany*

ARTICLE INFO

Keywords:
Lock-in thermography
Solar cell characterization
Depth-dependent investigation
3D analysis

ABSTRACT

Lock-in thermography (LIT) is the standard method for imaging and evaluating leakage currents in solar cells. For usually applied lock-in frequencies in the order of 10 Hz, silicon solar cells are considered to be thermally thin. Hence, depth-dependent investigations, as they are performed in non-destructive testing and failure analysis of ICs, were not performed until now by LIT. In this contribution two special LIT investigation and evaluation methods are introduced, which have the potential to judge whether some recombination occurs at the top, in the middle, or at the bottom of a Si solar cell. Such investigations can be useful to evaluate e.g. metal-induced recombination or the influence of crystal defects in multicrystalline solar material on the emitter or backside recombination. The methods are tested at a cell containing a diamond scratch in the emitter and backside recombination at the Ag back contact.

1. Introduction

The technique of lock-in thermography (LIT), which is widely used in non-destructive evaluation (NDE) [1,2], is also established in solar cell research for imaging and quantitatively evaluating inhomogeneous dark currents in solar cells [3]. While the primary goal of LIT in NDE is to "look below the surface", hence to detect hidden irregularities [2] and to estimate their depth below the surface [4], LIT investigations of solar cells and modules is used for imaging local heat sources. Until now such investigations have been evaluated only two-dimensionally. The reason is that, at the usual lock-in frequencies between 3 and 30 Hz, solar cells are considered as "thermally thin" [3]. This means that their thickness of typically 180 µm is small compared to the so-called thermal diffusion length, which is about 1.7 mm for silicon at 10 Hz [3]. Therefore the thermal waves cross the material vertically nearly undamped, and the LIT image of a heat source at the front of a cell equals that of a heat source at its backside. This is not strictly the case, in particular when examining the temperature distribution close to a point source or sharp edge of the heat source, see [5].

It would be interesting to check also in solar cells whether a local heat source is located at the top (close to the emitter), in the middle (in the bulk), or at the bottom of a cell (at the back contact). As a rule, the recombination in the free emitter (outside of the metallization) or at the back contact is assumed to be homogeneous. However, there are indications obtained by CELLO [6] that the back contact recombination velocity in multicrystalline (mc) solar cells is inhomogeneous, and dark lock-in thermography (DLIT) investigations have indicated that also the recombination in the metallized emitter of mc cells may depend on the bulk lifetime [7]. For cross-checking these results, LIT investigations with depth resolution would be desirable.

Also in failure analysis of integrated circuits LIT is used for detecting the depth position of faults causing local heat sources [8]. In this so-called "3D analysis" the measurement of the phase of the LIT signal for various lock-in frequencies allows one to determine the depth of the heat source below the surface. This investigation, however, is not performed on massive silicon material but on stacks of several thin dies (chips) glued together. Here the glue layers between the dies lead to a measurable and frequency-dependent phase shift if the thermal wave travels from die to die, which is evaluated. Moreover, in these investigations the heat sources can be assumed to be point-like, hence their geometry is known. This is not the case for the investigation of solar cells, where the local heat sources (recombination sites) have an irregular and generally unknown geometry. It will be demonstrated in the following section that this source geometry strongly influences the local phase of the thermal waves much stronger than the depth position. Therefore, and since the depth-dependent phase differences are much smaller in solar cells than in stacked ICs, the previous 3D evaluation method [8] cannot be applied here.

In the following section the physical problem to be solved is described in more detail and the simulation and evaluation methods are introduced. Then in Sect. 3 two different methods will be introduced that may allow to check whether a local heat source is at the top, in the

---

[*] Corresponding author.
E-mail address: breiten@mpi-halle.mpg.de (O. Breitenstein).

https://doi.org/10.1016/j.solmat.2018.05.009
Received 5 April 2018; Received in revised form 2 May 2018; Accepted 4 May 2018

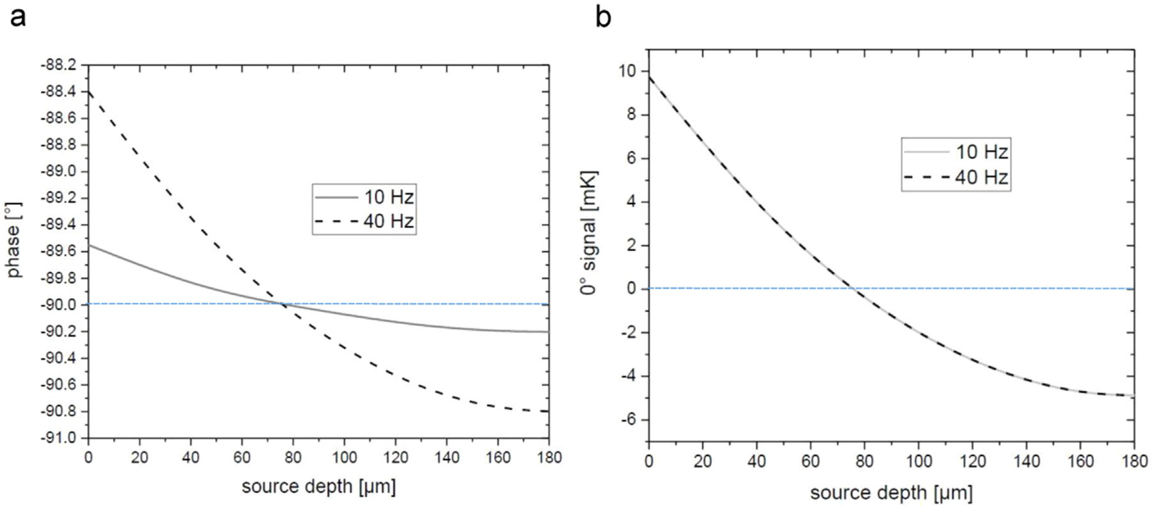

Fig. 1. (a) Phase signal and (b) 0° (in-phase) signal of a homogeneous heat source (1 mW/pixel) at 10 and 40 Hz as function of source depth in a 180 µm thick Si substrate.

middle (hence in the bulk), or at the bottom of a solar cell. These methods will be verified by simulations. In Sect. 4 these methods are tested on a solar cell containing a scratch at the top and preferred recombination at the Ag contact at the bottom. The results will be discussed in Sect. 5.

2. Simulation and evaluation methods and results

Deconvolution of LIT images can be used to deduce the power density distribution of the sample under investigation [3]. This task was performed here using DECONV [9]. This tool can perform two tasks: (1) It can simulate LIT images for a given pulsed power density distribution by performing a spatial convolution. (2) It can be used to evaluate given (experimental or previously simulated) LIT images by performing a spatial deconvolution, leading to the power density distribution that was responsible for the LIT images. The point spread functions (PSFs) necessary for the convolution and deconvolution are generated by DECONV for different sample geometries and lock-in frequencies, based on the formalism and specific functions developed in [5]. Possible source geometries are thermally thin samples, thermally thick samples, samples with a finite thickness, and finite and infinite thick samples with a highly conducting layer (HCL) on top. The latter option was developed for evaluating thin film silicon solar modules on glass [5]. The substrate thickness, the depth of the heat source below the surface, and the observation depth (where the temperature- (T-) modulation is detected; e.g. at the top or at the bottom) can be chosen, but all heat sources are assumed lying in one plane at the same depth. The substrate and HCL properties (thermal conductivity, density, specific heat capacity), the pixel size, and the lock-in frequency can be chosen.

DECONV allows to perform deconvolutions by an iterative and, what is used in this contribution, by the fast Fourier transform (fft) method using the Wiener filter, see e.g. [3]. The fft method generally works in complex number space. First, the software converts the DLIT images and PSFs in real space $T(x,y)$ and $PSF(x,y)$ into their Fourier transforms in frequency space $t(u,v)$ and $psf(u,v)$. For these Fourier transforms a convolution is a simple multiplication and a deconvolution, leading to the Fourier transform of the power distribution $p(u,v)$, is a division. In the presence of noise, the Wiener filter method replaces this division by:

$$p(u,v) = \frac{psf^*(u,v)\,t(u,v)}{|psf(u,v)|^2 + K} \tag{1}$$

Here $psf^*(u,v)$ is the complex conjugate of $psf(u,v)$. For $K = 0$ this is equivalent to $p(u,v) = t(u,v)/psf(u,v)$. From $p(u,v)$ the power distribution in real space $P(x,y)$ is obtained by performing an inverse Fourier transform. Note that the parameter K defines the "degree of deconvolution". For increasing K the resulting power distribution appears increasingly blurred, but noise is increasingly suppressed. $K = 0$ means maximum possible deconvolution being accurate up to one pixel. In the presence of noise this setting leads to meaningless results. Since in the simulations in Sect. 3.2 no noise was considered, they were performed using $K = 0$, but for evaluating experimental images as a rule a finite K parameter has to be chosen.

The fft deconvolution can be performed in DECONV either in scalar mode, here only one LIT image is evaluated, or in complex mode. In the latter case two LIT images are evaluated at the same time. The in-phase (0°) LIT image is used as the real and the − 90° LIT image as the imaginary input. This deconvolution mode is considered as the most accurate one and outputs in DECONV a real result (which is the wanted power density distribution) and an imaginary result, which should be zero for all pixels since power density is not out of phase with the excitation of the sample in LIT.

Using the PSF as well as convolution and deconvolution fully describes the physical problem including the depth dependence. The most obvious way to extract the depth information from a heat source below the surface is to measure the phase of the temperature modulation at the surface, as it was done in [8]. For a thermal wave leaving a heat source, the phase reduces by 2π (= 360°) over a distance of 2π thermal diffusion lengths [3]. In silicon this would correspond for a wafer thickness of 180 µm and a lock-in frequency of 10 Hz (leading to a thermal diffusion length of 1.76 mm [3]) to a phase shift of 5.9°, which should be easily measurable. However, this holds only if the thermal wave travels in an extended body, as it is the case e.g. for horizontally travelling thermal waves in a solar cell. If we consider vertically travelling thermal waves in a wafer being thin compared to the thermal diffusion length, the thermal waves are multiply reflected at the surfaces and the resulting temperature modulation at the surface is a superposition of many thermal waves. This effect reduces the phase contrast between heat sources lying at the bottom and at the top of a wafer, which can be modeled using the PSF of a small but finite thickness sample (implemented in DECONV), where the heat sources can be assumed to lie at an arbitrary depth. Fig. 1(a) shows the result of this simulation performed for 10 and 40 Hz for a homogeneous heat source as a function of the source depth in a 180 µm thick substrate. Let us start by examining the phase signal. It is slightly above − 90° for depth zero and drops to below − 90° for increasing source depths. We see that the dependencies are non-linear and for 10 Hz the maximum phase difference is only 0.6°, but for 40 Hz it is 2.39°, which should be