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MEASUREMENT OF LOW FREQUENCY NOISE OF MONOCRYSTALLINE SILICON SOLAR CELLS

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Abstract – Noise measured across silicon single-crystal solar cells may serve as a non-destructive reliability indicator of the devices. The noise sources in monocrystalline solar cells has been described. The noise measuring system and the results of measurement of circular form cells (a diameter of 100 mm and a thickness of 360 μm) have been presented. The DLTS measurements performed on investigated solar cells approved the noise measurement results.

Keywords: noise measurement, silicon solar cell, reliability.

1. INTRODUCTION

Noise as a diagnostic tool for electronic component quality evaluation and reliability prediction (to screen out the potential failure devices with the defects causing an excess noise) has been widely accepted. The fundamental kinds of noise (thermal, shot and 1/f noise) are observed commonly in electronic elements. For low frequency excess noise types (such as burst noise or generation-recombination noise) the power spectral density of noise increases with stress and damage. The sensitivity of the excess noise to the latent defects is the reason to use the noise measurement for these purposes. The current noise spectral density was found to be a quadratic function of the forward current in the low injection region for semiconductor devices such as solar cells. The excess current is a dominant noise component in this region. In many solar cells manufactured on the basis of silicon single-crystals a burst noise occurrence has been also ascertained indicating the presence of dislocations in the p-n junction space charge region and metal impurities [1]. Therefore the burst noise measurement can be additionally used for the solar cell quality evaluation.

2. EXPERIMENTAL TECHNIQUES

We have investigated solar cells manufactured from silicon single crystals (n^+pp^{++} structures of Czochralski -grown silicon wafers with a nominal resistivity of 1÷3 Ω·cm). The p-active layer was boron doped to serve as a p^+ substrate. The wafers were of circular form with a diameter of 100 mm and a thickness of 360 μm. The emitter was phosphorus diffusion doped with a junction depth of 0.2 μm. Both front and back contacts were made by means of Ti/Pd/As alloying with an aluminium reflector induced on the rear side.

For the purpose of accelerated ageing, the samples were subjected simultaneously to a higher temperature (400 K) and an electric field corresponding to a reverse voltage of 3 V applied to the cells.

The I-V (transport) characteristics and the noise parameters of the forward and reverse biased samples were measured before devices stressing and, subsequently, after subsequent stressing periods (of some thousand hours long). Additionally, in order to assess the suitability of noise parameters for the quality, reliability and life-time testing, correlation between the initial noise parameters and those after stress was evaluated.

A current noise spectral density can be measured as a noise voltage across the load resistance. In this case the ratio of the total measured noise to the inherent measurement system noise has the maximum value in the power matching conditions. For the forward bias it occurs when a noise source internal resistance of a measured p-n junction is equal to the load resistance.

It can also be measured directly using ultra low noise transimpedance preamplifier. The configuration of the preamplifier should be carefully designed (mainly its op -amp part and the feedback resistor dominating in its noise properties) depending on the solar cell impedance.

Noise characteristics were measured in the computer aided noise measurement system in a frequency range up to 10^5 Hz. The battery biased circuit for a solar cell noise measurement assures the maximum ratio of the measured noise power to the inherent system noise power and suppress spurious effects. The whole analogue part of the system is totally battery supplied and contains especially shielded, low noise voltage preamplifiers (for noise signals driven from low impedance sources) or current-to-voltage (I/V) converters (for high impedance noise sources). A properly selected configuration of the measurement system enables to achieve an enough high level of a measured noise signals from the device under test to be processed in the digital part of the system. The equivalent input noise voltage of the system voltage preamplifier (parallely connected opamps AD797) was estimated as $\approx 0.67\, nV/\sqrt{Hz}$ whereas the equivalent input noise current of the transimpedance preamplifier (OP 128 as the current to voltage converter) as $\approx 41\, fA/\sqrt{Hz}$ for the feedback resistor R_F of the converter having the resistance *10* MΩ. The results of the noise analysis were confirmed experimentally. The inherent noise of the measuring system can be subtracted from the results of the noise measurements. The final amplification factor is settled by means of the output amplifiers.

The digital part of the sytem includes the antialiasing filter SCXI-1141 (having eight software-controlled input channels with the software-selectable cut-off frequency $f_a = 100/m$ kHz, where m is an integer - $m \geq 4$) gives an output signal range ±5 V. The low noise and low distortion Dynamic Signal Acquisition Board PCI-4452 (used optionally instead of AT-MIO16 for noise characteristics estimation in the wider frequency range) simultaneously digitise input signals (within the range from ±10 mV to ±42.4 V) by means of a 16-bit resolution, 64-times oversampling, delta-sigma modulating Analog Digital Converter (ADC) over a bandwidth from DC to 95 kHz. The data can be next processed on-line or stored on a disk as time series with a required number of samples according to the accuracy of noise parameters and characteristics estimation.

The computer-controlled system (the virtual instruments for acquisition and processing of noise signals) operates under the LabVIEW software [2]. Before starting a noise measurement the system enables an initial monitoring of the measured noise waveforms transposed to its input to properly choose the required gain.

Spectra of low-frequency noise in monocrystalline silicon solar cells are also investigated at different illumination intensities at 300 K [4].

For verifying the noise measurements the technique of Deep Level Transient Spectroscopy (DLTS) has been used enabling to show an inhomogeneity of measured samples. The DLTS measurements were performed using a modified DLTS-81 Spectrometer system [3] with samples inserted in a liquid nitrogen cryostat cycled between 77 K and 400 K (the temperature was swept at a rate of 0.01 $K{\cdot}s^{-1}$). The quiescent reverse bias –10 V, the filling voltage pulse amplitude –9 V and the pulse width 50 μs was applied. The capacitance transients were digitized, stored and analysed in a measuring instrument connected directly to PC to extract the parameters of traps. According to the emission rate formula the Arrhenius' plot may be derived. From the temperature of the peak maximum one can determine the trap activation energy.

3. RESULTS AND DISCUSSION

The solar cells have been cut to obtain samples from the different area of the solar cell surface. Their properties hardly depend on the sample location. V-I characteristics of two different samples are shown in Fig. 1.

The sample No. 6/1 was taken from the area near the solar cell edge, whereas the sample No. 6/5 was cut out from near the centre where maximum inhomogeneity was confirmed.

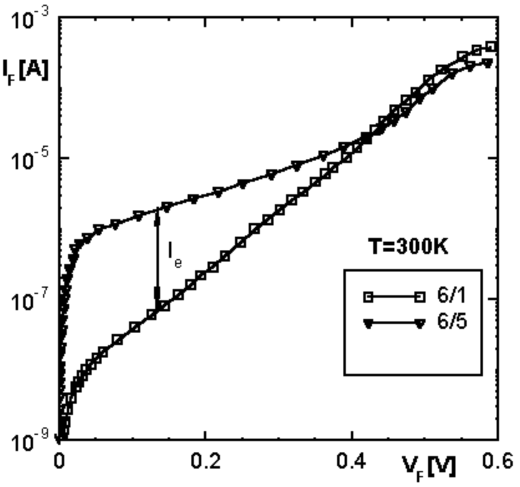

Fig. 1. V-I characteristics of silicon solar cell samples at room temperature

The excess current noise is a dominant current component in the low injection region. The selected results of noise measurements shown in Fig. 2 indicate sample No. 6/5 inferior quality in comparison to sample No. 6/1. The power spectral density of noise at low frequencies (measured across a load resistor 100 Ω at a voltage 0.2 V) for sample No. 6/1 is more than an order of magnitude lower than for the sample No. 6/5. It was confirmed at forward bias voltage up to $V_F = 0.4$ V. The sample 6/1 shows a $1/f^{\alpha}$ type component only (α is near unity) masked by the thermal noise at frequencies over 10^3 Hz. The sample No. 6/5 exhibits an $1/f^{\alpha}$ component at frequencies of up to 10^3 Hz, whose magnitude is however higher by two orders. In the frequency range from 10^3 Hz to 10^4 Hz a generation-recombination noise was observed.

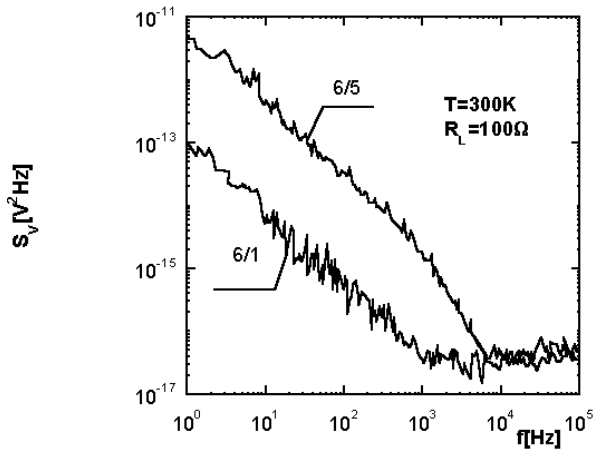

Fig. 2. Voltage noise spectral density $S_V(f)$ vs. frequency

The correlation factor is growing up with the stressing time. The strong correlation (correlation factor 0.82) between the noise current spectral density and the solar effectiveness parameter after 5000 hours of stressing is shown. The samples showing low noise have high conversion efficiency. Therefore we recommend to apply the measured noise parameter for the solar cell lifetime prediction and, generally, the reliability approval.

Burst noise was observed on a number of solar cell samples (Fig. 3). It was the most often two state Random Telegraph Signal (RTS) with a long time constants from 10 to 200 ms. The source of the noise consist of defects in the space charge region of the p-n junction.

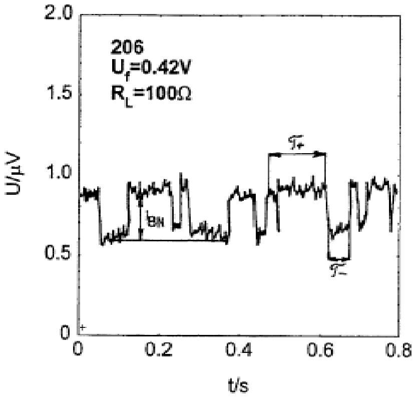

Fig. 3. Typical time waveform of the RTS noise at a constant forward bias with $U_F = 0.4$ V

It was found that under illumination the fluctuations of the photovoltage make the essential contribution to the excess noises. These fluctuations are generated in the space charge region and their peculiarities depend not only on the voltage bias but also on the level of illumination L (the illumination current) . A variety of other characteristics of the silicon solar cells are found to be conditioned by illumination level.

The current - voltage (I-V) characteristics of the silicon solar cells are dependent on the level of illumination where in forward direction an increase of the photovoltage is obtained. However in reverse direction an increase of the photocurrent occurs with increasing level of illumination.

For the same silicon solar cells the capacitance - voltage (C-V) characteristics were also measured under different illumination intensities at a constant frequency. It was found that the capacitance under different illumination levels is decreased for increasing illumination (to be 25% from its initial value).

The influence of illumination on the level of excess noises was investigated. It has been found that the level of noise spectrum increases with increasing L which is caused probably by the increase of the ohmic leakage conductance $G_{leak.}$. The leakage current originates from the volume current, transport along the precipitated lines covered by metallic impurities, and partially also by surface phenomena. The increase of L leads to a rise in the photovoltage (i.e., the increasing in photocurrent) noise, and observed peculiarities of this noise allow to conclude that the changes in space charge region properties take place under illumination.

In addition, DLTS measurements performed on investigated solar cells approved the noise measurement results. The inhomogeneity in the doping concentration especially at the centre of the solar cell area was confirmed [4]. For the central sample an energy level was measured as 0.40 eV (electron trap) and an activation energy as 0.80 eV (hole trap due to Fe impurity). For the edge sample hole traps exist at the energy level 0.80 eV.

The measurement results for other samples showed an evident correlation of all measured parameters orresponding to the samples from homogeneous area of the wafer and of the same parameters of the samples from inhomogeneous area.

The ratio of 1/f noise current spectral density S_I multiplied by frequency f to the forward current squared I^2

$$F_Q = S_I f / I^2 \tag{1}$$

can be used as an indicator of sample quality and reliability.

4. CONCLUSIONS

From the noise measurement results that the noise power spectral density related to defects is of 1/f type and the current noise spectral density is proportional to the square of DC forward current at the low injection mode. Samples with lower noise have higher efficiency. The average level of the noise spectral density of the entire ensemble increases with stressing time. The screening parameter was used to evaluate the correlation between the spectral density and the light conversion efficiency. It has been found out that there is a strong correlation between the initial-state noise and the conversion efficiency after 5000 hours of combined stressing. Good correlation among all three techniques, i.e. V-I characteristics, the noise spectral density and DLTS confirmed the noise measurements as characterization tools for the solar cell quality and reliability assessment.

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