SHEET RESISTANCE IMAGING (SRI) – A CONTACTLESS AND SPATIALLY RESOLVED METHOD FOR THE DETERMINATION OF DOPING INHOMOGENEITIES

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ABSTRACT:
Sheet Resistance Imaging (SRI) is an optical method for the investigation of doping concentrations and inhomogeneities. The measurement principle is based on the interaction of free carriers in silicon and radiation in the mid-IR.
By using a camera sensitive in the infrared SRI is the first measurement technique for emitter doping that realizes spatial resolutions of some 100 µm on all common wafer sizes with measurement times of a few seconds only. As SRI is a contactless and purely optical method, the principle restrictions in spatial resolution of four-point probing are overcome.
The most obvious application is the investigation of inhomogeneities in standard emitter diffusion. Thanks to the very high spatial resolution achievable (below 50 µm), SRI is very well suited to the detailed study of selective emitter structures. Additionally, an example of SRI measurements on high low junctions (e. g. back surface fields) is discussed.
As SRI is a purely optical measurement technique inhomogeneities in roughness of the sample surface are of utmost importance and may lead to erroneous results. Possibilities for avoiding and suppressing such effects are discussed and significant progress towards the application of SRI on alkaline etched multicrystalline silicon samples is demonstrated.
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1. INTRODUCTION

Sheet Resistance Imaging (SRI) is a recently introduced technique for the investigation of doping concentrations in heavily doped layers of solar cell precursor.
The general idea is that intrinsic silicon is nearly transparent in the mid-infrared (3-5 µm) but that free carriers present in the sample are able to absorb and emit IR-radiation. Thus measuring the IR-absorption or IR-emission from the sample in the dark may give information about the doping concentration. If two measurements are taken, one with the heavily doped layer present and one without, then the difference between these two measurements yields the IR absorption and thus information on the doping concentration of this layer.
The idea of measuring doping densities of heavily doped layers in silicon by this principle was already described by several authors [1-3], nevertheless all techniques proposed were only capable of measuring the sheet resistance as an average value over a (small) area of the sample under investigation. Using a CCD-camera sensitive in the infrared for measuring doping densities with a high spatial resolution was first proposed in Ref. [4],[5]. Development into an applicable measurement technique – Sheet Resistance Imaging (SRI) – was first presented in [6].
The first section of this paper will briefly describe the measurement principle of SRI. In the following sections different applications will be discussed. In particular the applicability to standard emitters, selective emitters and high low junctions (e.g. "back surface fields" - BSF) will be investigated. Finally, we will present results on materials with rough surfaces.

2. MEASUREMENT PRINCIPLE

A typical measurement procedure for heavily doped layers (e.g. emitter or BSF) consists of

- a measurement of the undiffused sample
- a measurement after in-diffusion of the heavily doped layer
- calculation of IR-absorption due to the heavily doped layer as difference between the two images obtained
- evaluation of resulting data for carrier concentration and/or sheet resistance.

Alternative to the measurement of each sample before diffusion, one sample per batch can be excluded from the diffusion and be used as a reference. The difference in transmission or emission is then calculated between the measurement on this reference and all samples under investigation. If this alternative procedure is applied, care has to be taken, that base doping, surface conditions etc. are the same for the reference and the samples under investigation. Both procedures allow routine investigations on the order of a few seconds per wafer.
The main components of the setup realized at Fraunhofer ISE are an IR-sensitive camera that features a NETD (noise equivalent temperature difference) of 17 mK and an array of 384x288 pixels and a hot- or coldplate as background for Absorption- or Emission-SRI, respectively.
A schematics of the measurement setup is shown in figure 1.
With this setup measurements of e.g. 125x125 mm² samples with a spatial resolution of about 440 µm are attainable in a few seconds. Upscaling the setup for larger samples reduces the spatial resolution proportionally (e.g. about 550 µm for 156x156 mm² samples) and has no adverse influence on measurement times. Additionally, the measurement is contactless and purely optical.
Taking the difference between transmission or emission measurements of the sample before and after diffusion ensures that the primary data obtained is exclusively due to the interaction of free carriers with IR-radiation. Unfortunately, this primary measurand is not proportional to the integral (over sample thickness)

doping concentration of the diffused layer under investigation as would be a first, naive guess. The complications involved are due to free carrier absorption in heavily doped layers not being directly proportional to the doping concentration [7]. Thus, in particular for layers with a prominent depth profile of the doping concentration, an appropriate modeling of the correlation between doping profile and integral free carrier absorption has to be done. Appropriate techniques for this purpose were developed elsewhere [6], [7].

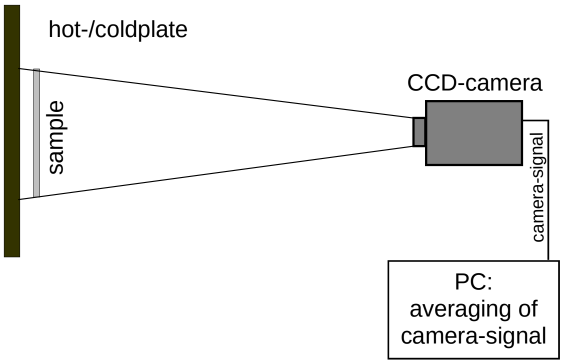

Fig.1: Schematics of the setup for Sheet Resistance Imaging (SRI).

In general, two measurement modes may be realized: Absorption-SRI and Emission-SRI. For the Absorption-SRI mode a hotplate behind the sample serves as IR-radiation source and the camera essentially measures the transmissivity of the sample in the wavelength range between 3 and 5 µm. This mode uses the additional absorption of IR-radiation due to the free carrier density of the layer investigated for the measurement.

The emission-SRI mode takes advantage of the free carriers to emit additional IR-radiation. In the emission-mode two different setups may be realized: In the first setup a coldplate has to be used as background such that the transmission of IR-radiation through the sample is effectively suppressed and the camera essentially measures the IR-emission by the free carrier concentration. A second experimental setup realizes a state, where the emission by the free carrier concentration dominates: the IR-image is achieved by heating the sample, e.g. on a hotplate and using a mirror as background. In this way the background IR-radiation corresponds essentially to room temperature, whereas the IR-emission of the sample is considerably higher.

The theory and general idea of distinguishing between Absorption- and Emission-SRI as well as finding optimal measurement conditions is essentially the same as for CDI and described elsewhere [8].

3. CONTROL OF DOPING HOMOGENEITY

3.1 Standard Emitter Diffusion

The homogeneity and possible drifts in the emitter diffusion may be controlled by means of sheet resistance imaging. The standard SRI method as described above may be applied for this purpose.

Figure 2 shows an example for such a measurement. This sample belongs to an experiment where different lamp arrays for the old prototype walking-string-furnace at Fraunhofer ISE were tested. Thus the homogeneity of R_{Sheet} is not state-of-the-art. Nevertheless the measurement is a good example for the possibility to characterize different experimental arrangements with SRI and thus contributes to the process of finding the best diffusion conditions. The image in figure 2 reveals a strong decrease of doping concentration towards the side-walls of the furnace. The homogeneity in transport direction is considerably better. The base material used for this experiment was 0.8 to 1.2 Ohmcm FZ-silicon. Obviously, investigations like the one presented in figure 2 can in principle as well be done with standard four-point probing. However, after the setup is once calibrated for the type of diffusion investigated, SRI allows to investigate the impact of tens of different sets of process parameters on the absolute value and homogeneity of emitter sheet resistance within just a few minutes. If done with four-point probing, similar investigations with a comparable spatial resolution typically take from several hours up to one or two days.

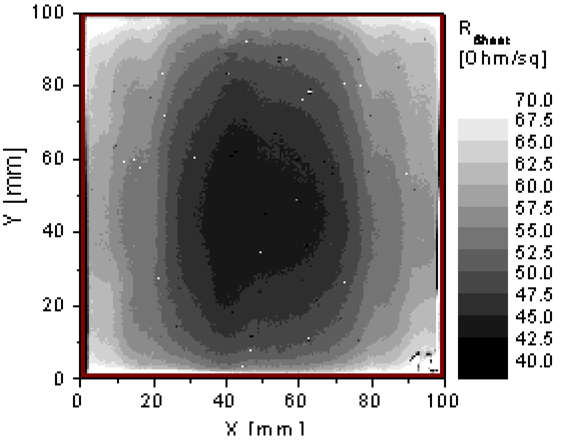

Fig. 2: Emitter sheet resistance of an inhomogeneous emitter diffusion investigated with SRI.

3.2 Selective Emitter

SRI features two main advantages: Firstly, extremely short measurement times as compared to four-point probing (discussed in section 3.1). Secondly, due to the purely optical measurement, SRI measurements can be done with a very high resolution. With the present setup true resolutions of 50 µm and below were realized. With an optimized IR-lense sytem resolutions of as low as 5 to 10 µm can be achieved. The spatial resolution in four-point probing on the other hand is always limited by the size and orientation of the probe head, that is essentially the distance of the individual probes within the array. Thus, typical true resolutions (not step-size) are on the order of many 100s of µm or often some mm.

This difference makes SRI especially suitable for the investigation of small sized structures in sheet resistance. An example is shown in figure 3, which displays a section of a selective emitter structure measured with SRI. The structure in doping concentration is clearly seen and extremely sharp compared to standard four-point probing.

This difference in resolution capability between SRI and four-point probing is observed in figure 4 as well, which shows a linescan over the sample in figure 3 where SRI and four-point probing are compared. The two setups for four-point probing represent different probe configurations showing the ambiguity in this method if the structure size of the sheet resistance is comparable to the size of the probe. The theory behind this ambiguity is outlined elsewhere [6]. It is observed that the problems concerning spatial resolution and ambiguity of measurement results on very small structures in sheet resistance, which are intrinsic to four-point probing, are overcome by SRI. Additionally – as expected from measurement conditions and principle – sharper edges of the emitter doping structure were found using SRI than with four-point probing. Thus SRI allows a reliable investigation of selective emitter structures.

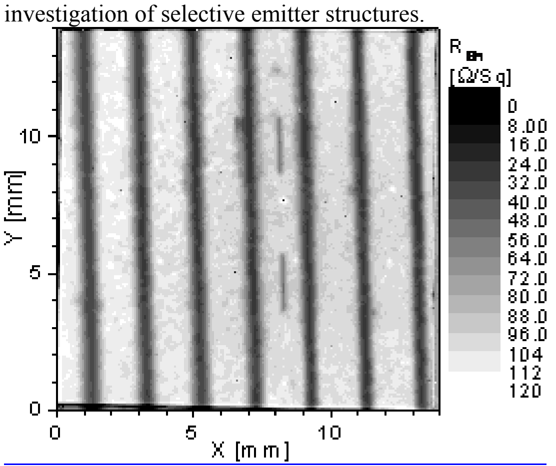

Fig.3 : SRI measurement of selective emitter structure.

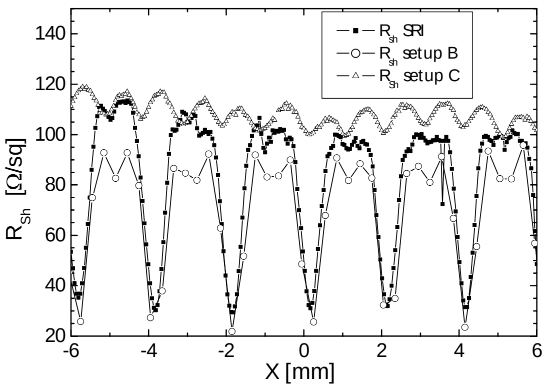

Fig. 4: Linescan of a SRI and two four-point probing measurements with different setups (same sample as in figure 3).

3.3 High-low junctions / "Back Surface Field"
Sheet Resistance Imaging is not just capable of measuring integral emitter doping concentrations. The same measurement principle may just as well be applied to other heavily doped layers. Of particular interest to solar cell processing is the investigation of high-low junctions, e.g. so called "back surface fields" (BSF). First measurements were performed on both, damage etched and textured monocrystalline silicon samples. Figure 5 shows the results obtained on a sample with a deliberately inhomogeneous (star-shaped) structure of the doping concentration.

4. INFLUENCE OF SURFACES

Up to now samples with optically high quality surfaces, that is polished or shiny etched mono-crystalline, were investigated. If samples with rough surfaces as e.g. alkaline etched multicrystalline silicon samples are to be investigated interference of the surface topology on different grains with the measurement signal may be expected: Comparable to (intentional) surface texture, roughness of the sample surface alters the surface reflectivity of the sample. This has two effects: Firstly, the transmission or emission (and thus the direct measurement signal) will depend on surface topology. Secondly, the pathlength of IR-radiation through the wafer – until it finally leaves the sample and is collected by the camera – is increased. This increase in pathlength results in an increased IR-absorption by an otherwise unchanged free carrier density in the sample and thus an – erroneous – increase in apparent doping density in SRI. An example for this effect is shown in the first row of figure 6: The upper left image displays the uncorrected transmission signal of an alkaline etched multicrystalline sample without any emitter diffusion. A significant difference in transmission on grains with different crystallographic orientation and thus different surface topology is observed. The upper right image displays the – uncorrected – SRI image obtained with the procedure as described in section 2. The emitter diffusion process is known to be very homogeneous. Except for a slight increase in sheet resistance towards the edges, four-point probing doesn't reveal a significant inhomogeneity as well. Nevertheless the apparent sheet resistance in SRI is mainly governed by the surface topology of the different grains and thus is essentially an artifact of the measurement.

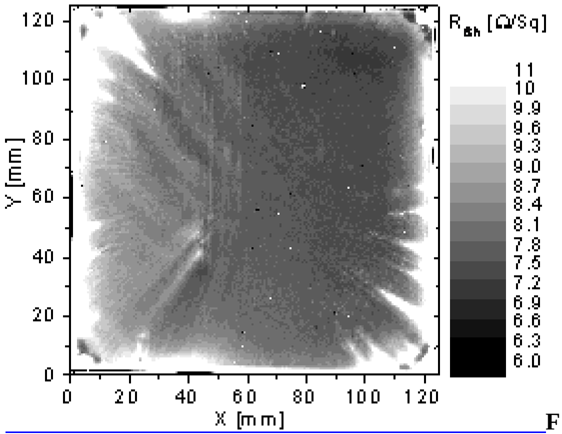

Fig. 5: SRI measurement of a so called back surface field.

As the apparent SRI results on multicrystalline silicon are typically erroneous as discussed above, correction algorithms have to be developed to make SRI applicable on all kinds of substrates. First results are presented in the second row of figure 6: Usually the two images to be subtracted do not match each other pixel accurate, as measurements are done before and after emitter diffusion on the same wafer or on parallel wafers with and without emitter diffusion. The lower left image is corrected for this effect by translation and rotation but otherwise shows the same SRI measurement as the upper right image. Note that most of the 3D-effect has disappeared but that grains of different surface topology still appear with different emitter sheet resistance. To correct this artifact advantage of the raw data (undiffused state) is taken. This is a measure for the local roughness of the sample surface topology. An empirical algorithm, which is under constant further development, was acquired, with which this image may be used to correct the measured apparent doping density image. The result of adding this correction is displayed in the lower right image of figure 6. Note that the different apparent sheet resistance in the area of grains with different surface roughness has almost completely disappeared. The remaining impression of the grain structure is mostly due to a residual 3D effect at the grain boundaries, which is most likely due to the use of a second parallel wafer as reference sample: No complete match of the two images can be achieved by translation and rotation only, since the grain structure may vary slightly from wafer to wafer. Note that all SRI images in figure 6 are scaled equivalently to facilitate comparison.

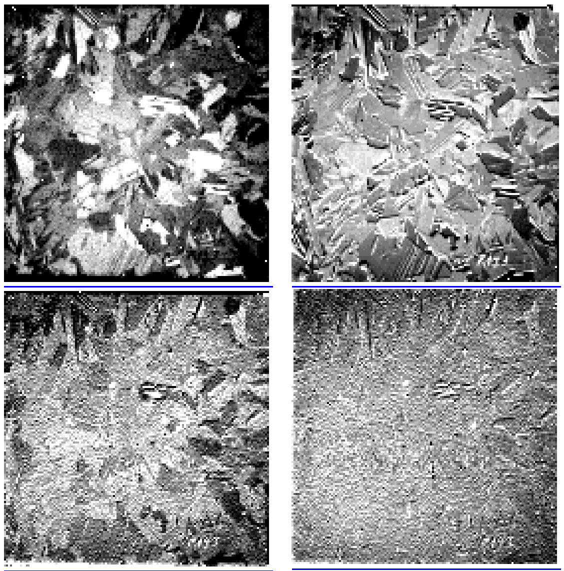

Fig. 6: Impact of surface topology on SRI measurements: Transmission image of alkaline etched multicrystalline sample (upper left) ; uncorrected standard SRI image (upper right) ; translation / rotation matched SRI image (lower left) and translation / rotation matched plus transmission corrected SRI image (lower right). All SRI images are scaled equally to facilitate comparison.

This procedure was applied to investigate the emitter sheet resistance of alkaline etched multicrystalline samples diffused in a continuous furnace. An example and comparison to four-point probing is displayed in figure 7. Good agreement between the two measurements is found demonstrating that the improved SRI technique is also applicable on materials with very inhomogeneous surface topology. The area of low sheet resistance to the left hand side of the sample is detected by both measurement techniques. The resolution of the SRI image in figure 7 was reduced from 288x288 to 97x97 pixels. This on the one hand further reduces 3D effects which are artifacts of the measurement and on the other hand proves, that even inexpensive cameras with a considerably lower spatial resolution than the one applied may be feasible for sheet resistance measurements.

5. CONCLUSION

The measurement principle of Sheet Resistance Imaging (SRI) is discussed. SRI is a contactless and purely optical measurement technique for the investigation of sheet resistance of highly doped layers. It combines high spatial resolution (typically some 100 µm) with very fast measurements of just a few seconds on all standard wafer sizes. SRI is demonstrated to be an extremely powerful tool in the investigation of all kinds of diffused layers, as e.g. emitters, selective emitters or high low junctions, in semiconductor processing and technology.

The optical measurement may on the other hand provoke problems and ambiguities if samples with rough surfaces as e.g. alkaline etched multicrystalline silicon are to be investigated. Procedures to correct the resulting measurement errors are demonstrated and will continuously be improved.

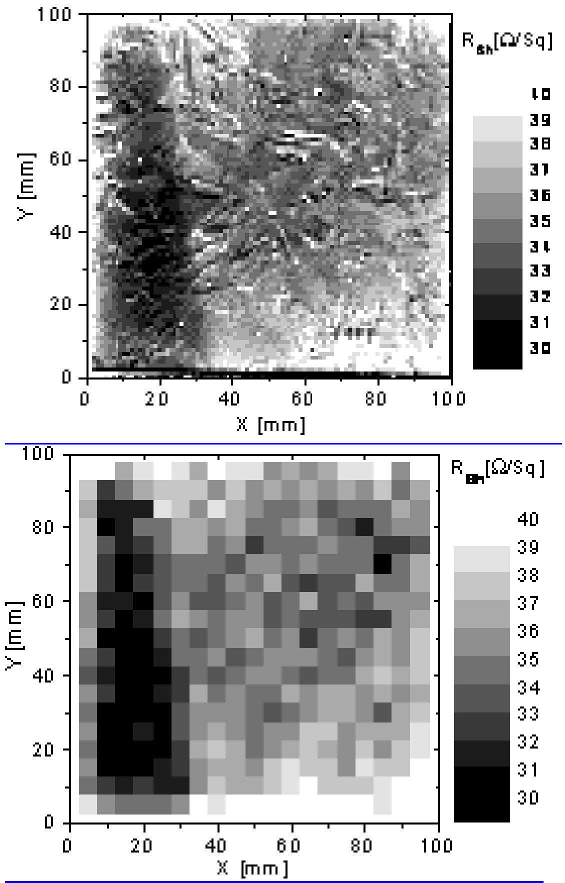

Fig. 7: SRI measurement (upper image) and four-point probing (lower image) of an alkaline etched multicrystalline sample with inhomogeneous emitter sheet resistance.

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