MAPPING OF DEFECT-RELATED SILICON PROPERTIES WITH THE ELYMAT TECHNIQUE IN THREE DIMENSIONS

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Abstract. The ELYMAT technique uses silicon electrolyte junctions as a Schottky-like contact for measuring photocurrents. It allows to map diffusion lengths as well as surface defects. New modes have been obtained by applying Lasers with different penetration depths and combining these measurements. This allows to extract information about the depth dependent bulk diffusion length as well as the recombination velocities of front and back surface.

Introduction

The ELYMAT (short for Electrolytical Metal Tracer) technique has been developed as an inline tool for manufacturers of Si wafers *and* for wafer fabs to allow a fully automated mapping of the minority carrier diffusion length (or life time) with a sufficient lateral resolution in a reasonable time [1, 2, 3]. The main drive behind this approach was the need to detect a contamination of the wafer with metals (life time killers) at a very low level (ppb - ppt range), and, if possible, to identify the contamination source by its ”finger print” in the life time picture. This appraoch was not without success, but competing methods, especially life time mapping with microwave absorbtion [4] or extensions of the surface photo-voltage methods [5] yield similar, albeit less directly interpretable, life time maps and do not require electrochemical knowledge and methods.

The strength of the ELYMAT technique lies in its possible extensions that go well beyond the relatively simple task of mapping diffusion lengths in a convenient range. In the field, more uses than just the visualisation of the life time distribution are emerging, cf. e.g., [6, 7, 8]. Monitoring the leakage currents of the Si-electrolyte junction or measuring very small variations of induced photo currents may provide valuable clues to manufacturing processes drifting out of specification [6], whereas measurements of the diffusion length as a function of injection levels helps to identify the chemical nature of the contamination.

New measurement modes are under development, either because new hardware becomes available (e.g. a suitable Laser with wavelength of 1040 nm and a respective penetration depth of 500 μm), or because certain properties of the Si-electrolyte contact are better understood. In addition, the combination of several independent measurements allow to obtain maps of the surface quality (usually displayed as surface recombination velocity S) as well as of the depth dependence of the diffusion length L and thus allows the three dimensional characterization of a Si wafer in unprecedented detail.

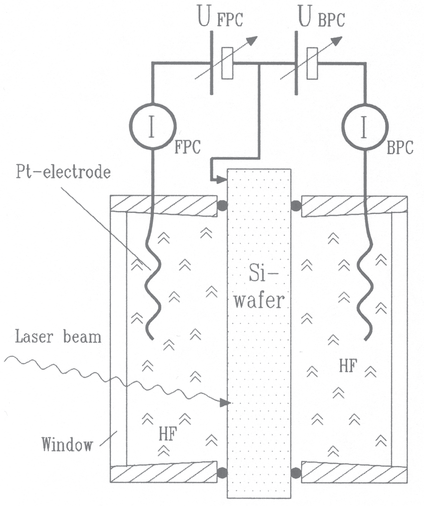

Figure 1: The electrolytical double cell of the ELYMAT. The two Si-electrolyte junctions can be biased independently; electrolytes other than HF are possible.

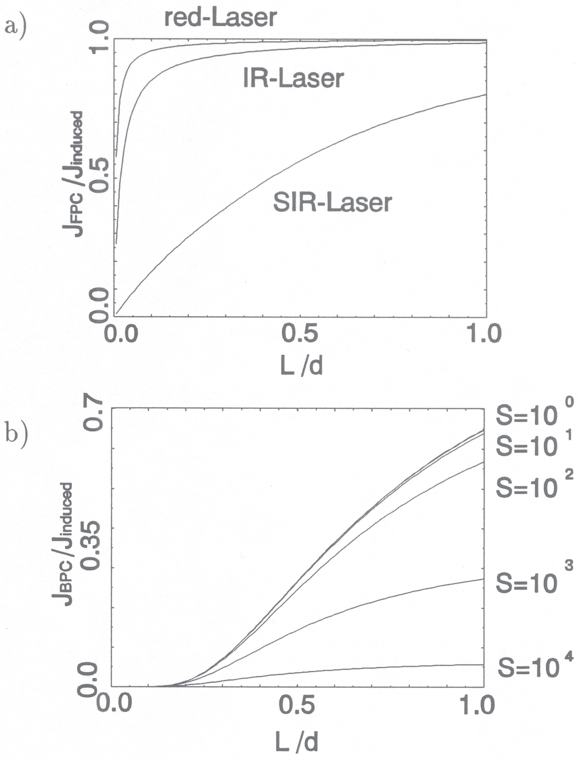

Figure 2: a) calculated frontside photocurrent (FPC) for different penetration depth (red Laser: 4 μm, IR-Laser: 13 μm, SIR-Laser: 500 μm); b) calculated backside photocurrent (BPC) for IR-Laser and different values of front surface recombination velocities $S \quad [cm/s]$.

Basic Set-up and Standard Modes

Fig. 1 shows a simplified cross-section through the heart of the ELYMAT, the electrolytical double cell. The Si wafer is in contact with a suitable electrolyte on front- and backside. The wafer as well as the electrolytes are electrically contacted by needles around the perimeter of the wafer, or Pt electrodes, respectively. Both Si-electrolyte junctions can be biased independently, the currents flowing on the frontside or backside of the wafer are the measured quantities in most cases. Since the junction behaves very much like a good Schottky contact if diluted HF is used as an electrolyte, proper biasing essentially allows to use a junction as a solar cell. The peculiarities of the Si electrolyte junction are described in [9] and have to be kept in mind, but are of no particular interest for the standard modes except for the convenient feature of the contact between (clean) Si and HF: Its interface recombination velocity is rather small and can be mostly neglected [10].

If minority carriers are locally generated by a Laser beam, they can be collected at the frontside of the wafer (frontside always defined as the illuminated surface) or at the backside. Front- and backside photo current measurements (FPC and BPC mode) as a function of the position of the Laser beam provide the basic modes of the ELYMAT. If S can be neglected, the current measured in both modes contains only the diffusion length as unknown quantity.

Fig. 2 shows the calculated dependence of the photo currents on the diffusion length (scaled to fractions of the wafer thickness d) with the parameters surface recombination velocity S_F at the frontside for BPC mode and penetration depth of the Laser beam for the FPC mode, respectivly. It can be seen that for a red Laser (wavelength = 640 nm, penetration depth = 4 μm) the FPC mode is insensitive to large diffusion lengths whereas the BPC mode fails for small L values. The interesting intermediate region of L may be hard to measure in this case. A Laser with a penetration depth of 13 μm is advantageous in this case, even better is a penetration depth of 500 μm provided by a 1040 nm Laser. The red Laser, however, has some merits in the FPC case, too. The current in this case is particular sensitive to defects in the space charge region and may pick up metal precipitations with extremely high sensitivity [6].

New Measurement Modes and Evaluation Techniques

Using Lasers with markedly different penetration depths allows independent measurements with significantly different depth distributions of minority carriers. The recombination behavior of a minority carrier depends on its depth position if the recombination at the surface can not be neglected or if the depth distribution of recombination centers is not uniform. Thus the currents measured will contain information about the surface recombination velocity on the front- and backside and about the depth dependence of the diffusion length ($L(z)$). Depending on the penetration depth of the light and the mode chosen, the sensitivity of the measured currents to these parameters is quite different. A FPC measurement with a red Laser, e.g., is practically totally insensitive to recombinations at the backside; this is also true for any BPC measurement since the space charge region belonging to the Schottky-like junction on the backside prevents surface recombination. A FPC measurement with the deeply penetrating Laser (dubbed SIR-Laser), however, is quite sensitive to the recombination velocity on the backside. Since we obtain up to 12 measurements (3 wavelengths, 2 measuring modes, front- and backside interchanged), the data is used to fit a model that allows for finite surface recombination velocities and two different diffusion length within the wafer. For sake of mathematical simplicity, $L(z)$ is approximated by a step function (which may not be a good approximation in some cases); these values as well as the depth of the assumed step are extracted from the raw data by a least square fitting procedure.

Using the regular modes, the data obtained contains some noise as, e.g., fluctuating leakage currents or unknown or fluctuating Laser intensities which adversely influence the computations. This problem is reduced in a new mode unique to the ELYMAT technique: Using the SIR-Laser and biasing *both* sides of the wafer as a minority carrier collecting junction (i.e. a FPC and BPC measurement is taken simultaneously), easily measurable currents are obtained, the relation of which can be shown to be almost independent of the intensity of the Laser and of certain noise contributions. Used as an additional input into the numerical calculation, the results are smoothed to a considerable extent and relatively small variations of S and L can be detected.

Another unique feature of the ELYMAT is the socalled "restricted photo current"-mode (RPC). In contrast to the above discussed modes the frontside current is measured applying a bias which is well below the value for photocurrent saturation. This RPC-photocurrent shows a strong dependence on the diffusion length L and surface recombination velocity S, which is not seen in the standard FPC-mode, but requires extensive theory for interpretation. In addition to the parameters L and S it is a function of parameters like concentration of the electrolyte and doping of the wafer and, making things worse, the relative influence of these parameters on the photocurrent depends strongly on the applied bias.

A particularily attractive feature of the ELYMAT technique is its extendability to multicrystalline Si in use for solar cell applications. The minority carrier diffusion length is the prime factor responsible for solar cell yields (and for costs of the material). The ELYMAT not only allows extensive characterisation of L (and S) but offers the possibility of high resolution measurements in lateral directions because the Laser beam can be focussed easily and the electrolyte is fully transparent. Since the measured quantity is a photocurrent, which is also the quantity of prime interest in solar cells, the results are directly and easily interpretable in terms of solar cell performance.

Experimental results

Fig. 3 a) and b) show the photocurrent maps obtained in the new mode where both FPC and BPC currents are measured simultaneously. Surface recombination can be safely neglected in this case; the visible features are predominately bulk. It should be noted that a rare artifact is also observed: The system of several concentric rings in the top half of the wafer of Fig. 3 a) is due to optical reflections. The other measurements which are used for the computations are, for lake of space, not shown.

Fig 3 c) and d) show computed maps of the diffusion length in the front or back region of the wafer; Fig 3 e) the calculated depth of the step where the change-over occures. In this particular case the diffusion length is considerably smaller in the region close to the polished surface, an observation which has been made repeatedly and which may indicate that chemical-mechanical polishing adversely effects diffusion length.

Fig. 3 f) finaly shows the surface recombination velocity map; it clearly denotes defects, probably scratches. The rather large values of S in this case may be due to the fact that this particular wafer was not cleaned and may well carry some (e.g. organic) contamination producing large values of S which are not compensated by the HF.

Fig. 4 a) shows first results of ELYMAT measurements with multicrystalline Si. All modes mentioned so far can be used for characterising this material. It is, however, more difficult to contact the thin ($\approx 300 \mu m$) and mechanically "weak" multicrystalline slices with needles. For lake of space only the possibility of obtaining reasonable high lateral resolution without any special optical means is demonstrated. Fig. 4 b) shows the corresponding structure of the

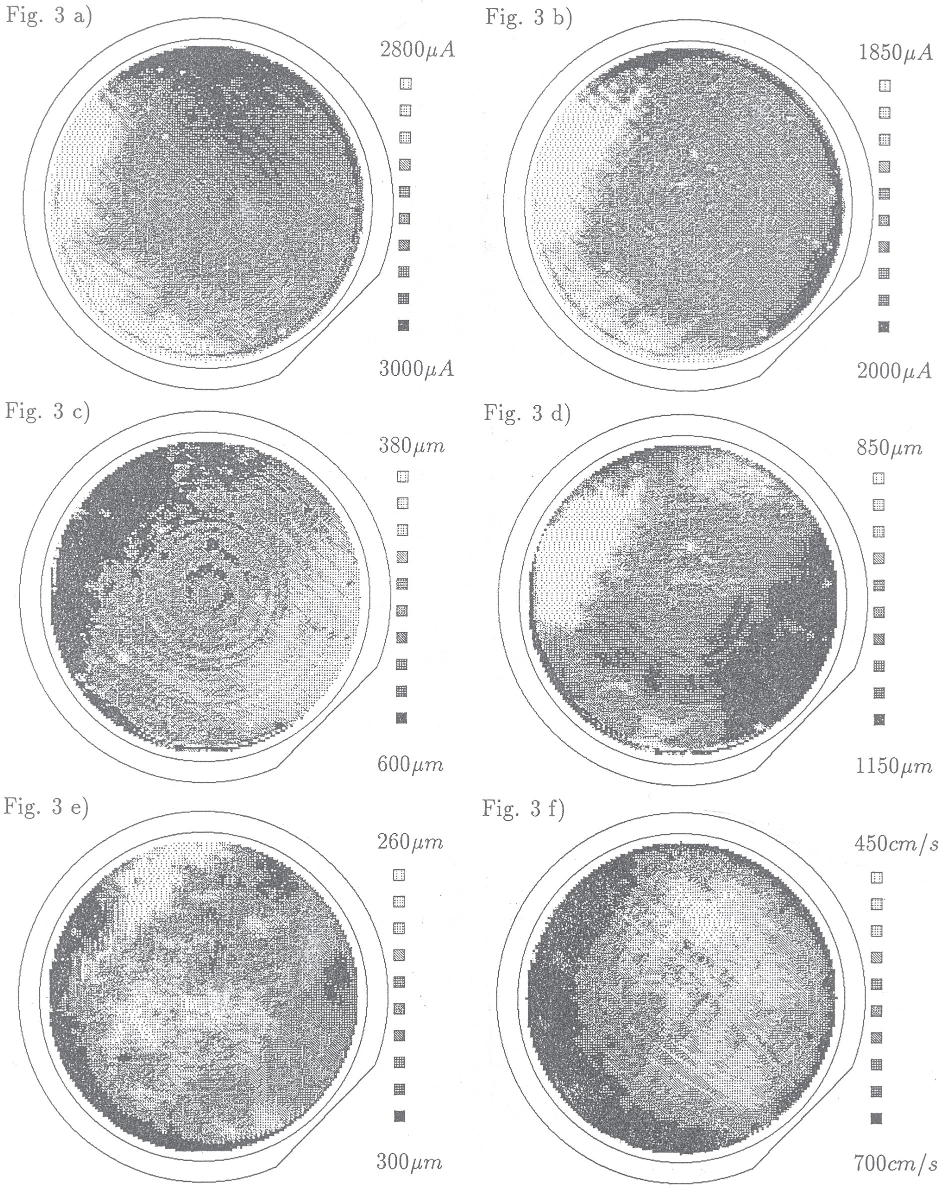

Fig. 3 a)

Fig. 3 b)

Fig. 3 c)

Fig. 3 d)

Fig. 3 e)

Fig. 3 f)

Figure 3: a) FPC and b) BPC measurement with SIR-Laser with both sides measured simultaneously; c) calculated diffusion length of the front half of the wafer; d) calculated diffusion length of the back half of the wafer; e) calculated depht of the step; f) calculated recombination velocity of the back surface.

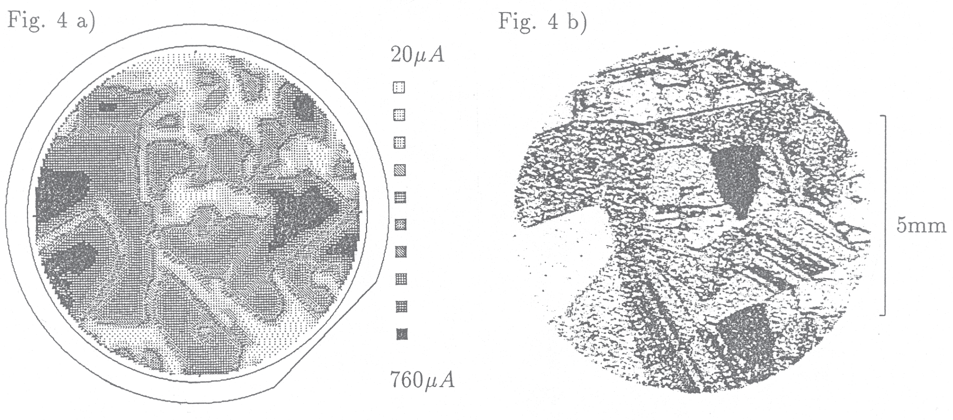

Figure 4: a) ELYMAT measurement of multicrystalline Si with higher lateral resolusion; b) corresponding structure of the specime obtained by a digital scanner.

specime simply obtained by a digital scanner. The correlations between electronic surface and bulk properties and crystal defects are clearly visible.

Summary and Conclusion

The ELYMAT principle allows to obtain three-dimensional information about the bulk and surface perfection of a Si wafer in several different modes. It was shown that maps of interesting properties as, e.g. surface recombination velocities or depth dependence of L, can be obtained by relating independent measurements of the well understood standard mode with the help of a complete theory.

An extension of the ELYMAT technique to multicrystalline Si is possible despite of some problems concerning the contacting of the wafer by needles.

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