COMPARATIVE STUDY OF LASER INDUCED DAMAGE IN SILICON WAFERS

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ABSTRACT

In this paper we present different possibilities like QSSPC lifetime measurements, x-ray diffraction and defect etch to measure laser induced damage in silicon wafers. The lifetime measurement results of the laser chemical etching (LCE), Laser Micro Jet^{TM} (LMJ) and a standard laser are plotted in a diagram. Furthermore the defect etch investigation was done with Yang etch and the etch pits are analyzed with scanning electron microscopy. In order to show the advantage of the waterjet guided laser and accordingly of LCE, we compare the LMJ/LCE laser grooves with a standard Nd:YAG scanning laser system for each method.

INTRODUCTION

For many applications it would be advantageous to get a better knowledge of the laser damaged layer. For example in the solar cell production the damage etch times could be reduced significantly by knowing the damage depths dependent on different laser parameters and laser systems.

For this reason many publications deal with the characterization of laser damages in silicon. Amer et al. determine the tensile stress induced by laser processing with Raman spectroscopy [1], [2]. Singh et al. [3] and Arora et al. [4] detect changes in the silicon surface due to laser induced damage via a HeNe laser reflection measurement. Abbott et al. visualized defects on a (100) silicon surface by the application of the Yang etch [5]. A lot of other defect etches for (100) surfaces can also be used to characterize crystal defects like line and point defects or dislocations for example Schimmel etch [6], Secco etch [7] and Wright etch [5].

Other defect analysis methods are photoluminescence measurements or transmission electron microscopy which needs a complex sample preparation. Laser acoustic wave technology (LAwave^{TM}) [8] from Fraunhofer Institute for Material and Beam Technology (IWS) uses the propagation of a surface acoustic wave on the silicon material. Damages cause the surface wave velocity to change, which is detected and the slope of the dispersion curve contains information about the depth of the damaged layer. X-ray diffraction is a non destructive possibility to measure the dislocation densities induced by laser processing. The full width at half maximum of the detector signal of the reflected light beam is used to calculate the dislocation density [9].

In this paper we will apply three of these methods to demonstrate the more gentle way of silicon ablation with the waterjet guided laser system and with LCE. Kray et al. [10] pointed out that LCE already performed better than LMJ for the investigated microstructuring but its potential is far from being fully exploited. Therefore we prepared also samples with LCE and optimized the laser parameter to reduce the laser induced damage. The QSSPC results mentioned below do not include the optimum LCE-parameters because the sample preparation for QSSPC measurements is time-consuming in comparison with defect etch or x-ray diffraction. It is more efficient to apply defect etch and x-ray diffraction for parameter optimization, because we get a faster result. The verification with QSSPC certainly has to be done in the future.

EXPERIMENTAL RESULTS

Lifetime measurements

To investigate the laser induced damage with QSSPC lifetime measurements, laser grooves were cut into a FZ silicon wafers with varying pitches. Afterwards the wafers were passivated and the effective lifetime τ_{eff} was measured. In the figures 1-3 $1/t_{eff}$ was plotted for every single pitch versus the fraction of the laser cuts. The slopes of the obtained straight lines give evidence of the specific recombination activities of the damage induced by the different processes. This means that the larger the slope of the straight line the more damage was induced into the silicon by the laser. The reference (dashed line) is an unstructured silicon wafer without damage.

To analyze the depth of the damage layer we etched the laser grooved wafers in stationary KOH solution with varying etch duration.

The results pictured in figure 1 and 2 were made with a standard Nd:YAG laser system and with the LMJ/LCE system respectively. In order to compare them with each other the laser parameters were selected in that way that the same groove depth was obtained.

Figure 1 shows the results of a standard Nd:YAG laser system with 1064 nm wavelength. The slopes for the unetched wafers and the 1 min damage etched wafers are nearly the same. After 5 min etch time a decrease in slope can be observed. Consequently after 10 min etch time the slope has a minimum but is still not in a damage free region. A longer etch interval is necessary to remove the damage completely.

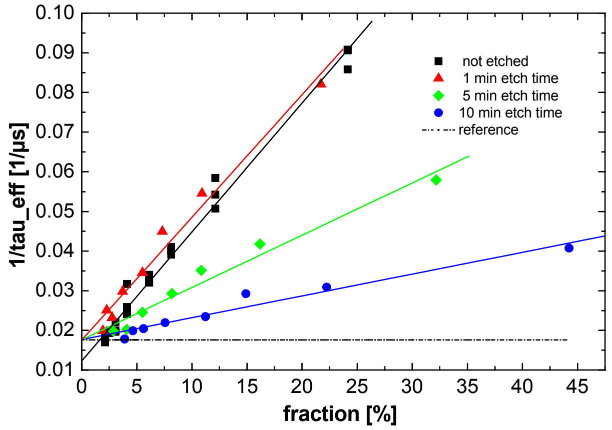

Fig. 1. Standard Nd:YAG grooved silicon wafers: Comparison of lifetime measurements of unetched and damage etched (varying time intervals) silicon wafers.

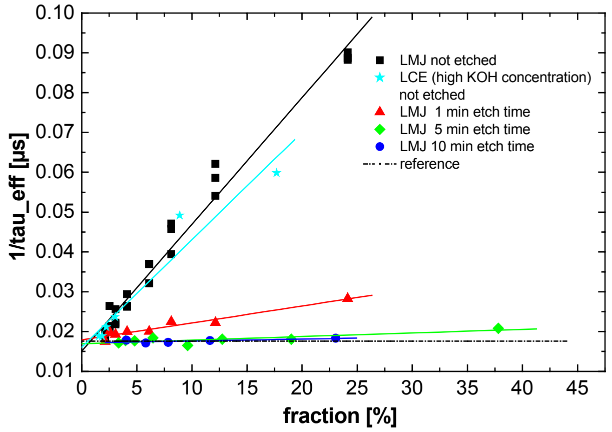

Fig. 2. Comparison of LMJ and LCE structured wafers: Lifetime measurements of unechted and damage etched (varying time intervals) silicon wafers.

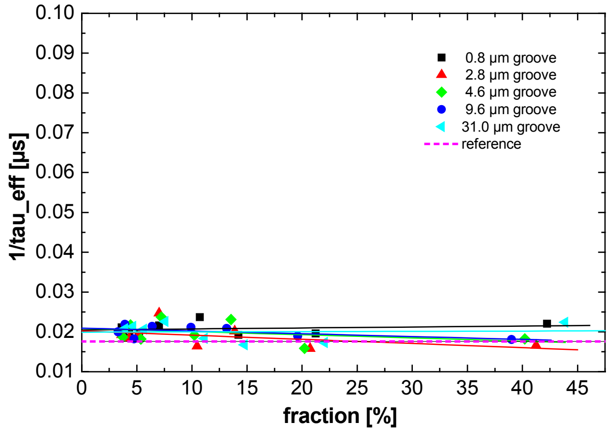

Fig. 3. KOH etched grooves: Comparison of different groove depths to evaluate the influence of the groove form.

Figure 2 depicts the results of the waterjet guided laser system and the LCE process, both done with a Nd:YAG 1064 nm. One can see that the unetched LMJ grooved wafers have the same slope as the unetched standard laser structured wafers in figure 1. From this point of view one can assume that the damage layer is alike for both systems. However even after 1 min damage etch the slope of the LMJ curve decreases strongly so that it is actually lower than the gradient of the 10 min etched standard laser grooved wafer. After 5 min etch time the grooves are already damage free. If we assume an removal rate of the KOH damage etch of approximate 1 µm/min, the damage depth induced by the water jet guided laser is less than 5 µm whereas it is larger than 10 µm for the standard laser system.

The slope of the LCE line fit, done with high KOH concentration, is lower than the one for LMJ, done with the same laser parameters. This indicates a smaller heat-affected zone but shows that these are not the optimum parameters for the LCE process yet. Changes in flow velocity, cutting speed, KOH concentration and KOH temperature have to be adjusted so that no damage is present even without damage etching.

To analyze the influence of the groove form on the QSSPC measured data reference wafers with KOH etched grooves (by means of photolithography) were produced. The pitches were comparable with those of the laser structured wafers and the groove depth was adjusted by the etching time. The depths vary from 0.8 µm till 31 µm and the form also vary from flat trapeze for little groove depth to sharp grooves at larger depth. Figure 3 shows that independent of the groove form and the groove depth the line fits are in the same region as the unstructured reference (dashed line). This demonstrates that the groove form has no influence on QSSPC lifetime measurements.

Defect etch

For this kind of analysis method the wafers were tempered with a rapid thermal process (RTP) and then Yang etched (25 °C for 2 min). The laser induced damages are transformed into dislocations by the short tempering which are visualized by etch pits resulting from the Yang etch.

Figure 4-6 show the results of the different laser cuts done with LCE, LMJ and standard laser. For a better comparison of the laser grooves scanning speed, repetition rate and energy density of the laser systems where the same. For all laser grooves one problem is obvious. There is deposition of molten and cooled down silicon in the grooves and especially for the standard laser groove also on the edges of the cut (figure 4 a). In contrast to this the LMJ laser groove has deposition only inside the groove (figure 6 a) and the best results are obtained with LCE which has a minimum of deposition in its groove (figure 5 a). Most of the depositions were etched by the KOH during laser processing. No side etch was observed although warm KOH was used. This means after impingement on the surface the KOH cools down very fast so no etching outside the groove can take place.

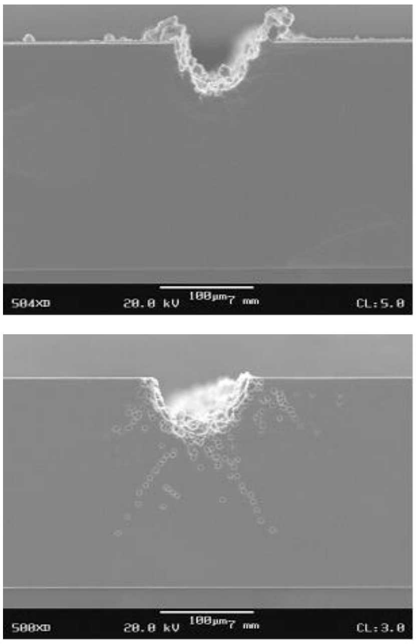

Fig. 4 a,b. Standard Nd:YAG laser groove done with 520 MW/cm^2. a) before tempering and Yang etch, b) after tempering and Yang etch. Etch pits in the silicon bulk mark dislocations caused by the laser induced damage.

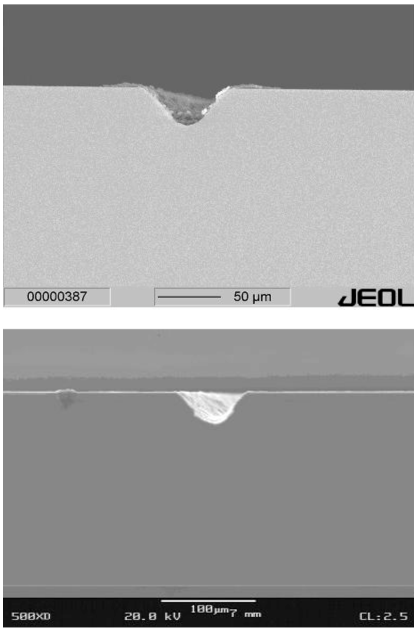

Fig. 5 a,b. LCE laser groove done with 520 MW/cm^2, high KOH concentration with medium temperature. a) before tempering and Yang etch, b) after tempering and Yang etch. No etch pits in the silicon bulk can be seen.

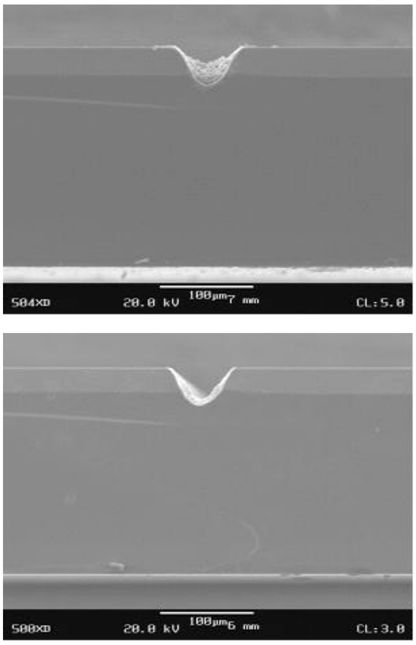

Fig. 6 a,b. LMJ laser groove done with 520 MW/cm^2. a) before tempering and Yang etch, b) after tempering and Yang etch. No etch pits in the silicon bulk can be seen.

After laser cutting and cross sectioning the wafers where tempered and Yang etched. LMJ and LCE (figure 5 b and 6 b) show no etch pits which demonstrates the gentle way of grooving for LCE but also for LMJ.

The advantage of LCE is the reduction of deposition of silicon in the groove which could supersede a damage etch if further improvements eliminate the remaining depositions. In contrast to this the standard laser induces enormous damage in the silicon wafer depicted in figure 4 b.

X-ray diffraction

The incoming x-ray beam is scattered at the lattice planes of the silicon crystal in the first few µm of silicon surface. A perfect silicon crystal generates a narrow reflection signal with a small full width half maximum. The peak of this signal describes the solution of the Bragg-law, it is the angle where constructive interference appears, called Bragg-angle. For the (004) plane of silicon this angle is $\Phi = 34{,}56°$. The signal becomes wider, if the crystal contains dislocations, because the lattice planes are locally deformed. This leads to an increase of signal intensity at angles different from the Bragg-angle, so that the full widths half maximum (FWHM) of the signal increases. Consequently the FWHM gives information about the dislocation density. The conversion from FWHM into dislocation density ρ_V is calculated with equation 1 after Hirsch et al. [9]:

$$\rho_v = 410 \cdot \Delta(FWHM)^2 \qquad (1)$$

For the investigation of laser grooves with x-ray diffraction we cut grooves with a defined pitch into a silicon wafer analogous to the lifetime measurement wafers. The fraction was 20 % for all samples. No further sample preparation was necessary then before the measurements. The results are shown in figure 7. The two bars on the left hand side display the dislocation densities for LCE samples with optimized and not optimized parameters at highest laser intensity. The bars on the right hand side show the dislocation densities for the standard Nd-YAG laser and LMJ at low laser energy. The values for the standard laser and the LCE with not optimized parameter lie in the same range. What we can see on scanning electron microscope pictures as depicted in figure 4 a and 6 a is that there is remaining molten silicon in the grooves and for the standard laser even at the groove edges. This is amorphous silicon and causes the FWHM of the x-ray diffraction signal to broaden and consequently the dislocation density increases. This means that for the LCE laser grooves with not optimized parameters the deposition in the laser groove is not etched away completely. By optimizing the LCE parameters the dislocation density decreases, which indicates a local etching in the groove. The molten silicon is efficiently etched during the cutting process by injecting the KOH onto the hot silicon. The so generated laser groove is free of deposition as shown in figure 8. This denotes that the x-ray diffraction measures the dislocation density of the direct groove surface and not of the molten silicon. According to what we found out in the defect etch section silicon bulk below the laser groove is clearly free of damage, see figure 7 LCE with optimized parameter.

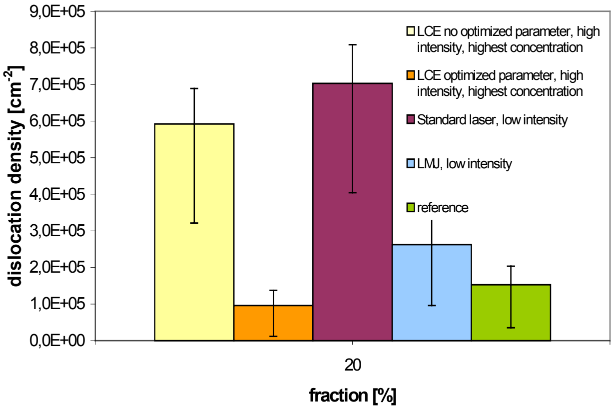

Fig. 7. Comparison of dislocation densities of LMJ/LCE and standard laser grooved wafers.

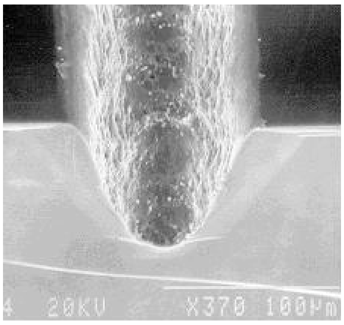

Fig. 8. LCE laser groove with optimized parameters

CONCLUSION

Different methods to analyze laser induced damage were presented. Laser cuts with standard laser, LMJ and LCE where performed to show the enormous advantages of the liquid guided laser systems. With Yang-etch we demonstrated a smooth removal by LCE and LMJ. With x-ray diffraction we deduced a damage free silicon removal for LCE with optimized parameter. From this result we conclude that the molten and cooled down amorphous silicon influences the measurement of x-ray diffraction and impeded to measure directly on the groove surface. With LCE the amorphous silicon was etched away and therefore the damage free surface of the laser groove could be analyzed with the x-ray beam. With optimization of laser and fluid parameters we achieved this reduction of silicon deposition within the laser groove which is one of the biggest problems of silicon laser ablation. The chemical etch medium has to be adapted further to avoid depositions of silicon completely.

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