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Investigation of laser irradiated areas with electron backscatter diffraction

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Abstract

In this work, two silicon nitride (SiN_x) layers with two different refraction indices, deposited on polished or damage-etched silicon wafers were locally irradiated by laser pulses. The focus was set on the investigation of the ablation mechanisms. Thereby, an ultra-short laser source (pulse duration 10 ps, wavelength 532 nm, Gaussian profile) was used. The irradiated areas were investigated by electron backscatter diffraction (EBSD) in order to analyze the near-surface crystallographic orientation and crystallinity.

In this work an indirect ablation was observed for SiN_x (n = 1.9). Further, a change from an indirect ablation to a partial lift-off for SiN_x (n = 2.1) was determined to be fluence dependent. At low fluences, the SiN_x was completely removed. However, at higher fluences, SiN_x was not completely removed, due to direct ablation. The two-photon-absorption coefficient of SiN_x (n = 2.1) was estimated to be $2 \cdot 10^5$ cm/TW.

Keywords: Laser processing; ablation; ultra-short pulse laser

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1. Introduction

Patterning processes of dielectric layers have been introduced to the production process of crystalline silicon solar cells. For the patterning of a dielectric layer, laser processes have become increasingly attractive due to the possibility of very high process speeds and accurate contact-free procedures.

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However, the ablation mechanisms are up to now not completely understood [1-5]. The following questions still have to be debated:

- How is a dielectric layer exactly ablated?
- Does absorption of the dielectric layer decrease the laser-induced damage in silicon?
- Is the dielectric layer within the laser irradiated area completely removed?

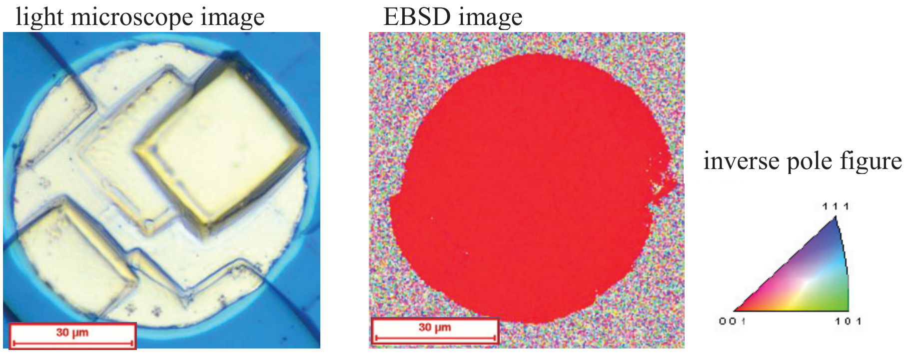
To answer these questions, the laser irradiated areas were investigated by electron backscatter diffraction (EBSD) in this work. Furthermore, light microscopy and atomic-force microscopy (AFM) were used for investigation. In addition, the absorption coefficients of the SiN_x layers were measured by spectral ellipsometry.

2. Electron backscatter Diffraction (EBSD)

Electron backscatter Diffraction (EBSD) [6] analysis has been performed in a Tescan Lyra XMU dual beam microscope equipped with an EDAX/TSL XM4 camera. The information about the crystallographic orientation originates from region near the surface. The depth of this region strongly depends on electron acceleration voltage. Hence, experiments were carried out with thin amorphous silicon layers deposited on monocrystalline silicon wafers. This investigation revealed that detecting the crystallographic orientation of the underlying crystalline silicon wafer is just possible for amorphous silicon layers thinner than approx. 15 nm and approx. 40 nm at 10 kV and 30 kV, respectively. This dependence is also valid for SiN_x.

In this work, two different SiN_x (thickness: 100 nm; refraction index 1.9 and 2.1) layers were deposited on planar p-type monocrystalline (crystal orientation [100]) silicon wafers by using PECVD. The samples were locally irradiated by single laser pulses. The laser was a $Nd:YVO_4$ laser with a wavelength of 532 nm and a pulse duration of 10 ps.

Fig. 1 and Fig. 2 show EBSD images for these SiN_x layers (Fig. 1: n = 1.9, Fig. 2: n = 2.1). The accumulation of red pixels indicates silicon with [100] crystal orientation whereas pixels with varying colors stems from areas with no measurable crystal orientation, such as amorphous regions. In Fig. 1 crystalline silicon is visible after laser irradiation with a fluence F_0 of 1850 mJ/cm².


light microscope image

EBSD image

inverse pole figure

Fig. 1. EBSD image after laser irradiation (F_0 = 1850 mJ/cm²) of SiN_x layer (n = 1.9); information depth approx. 15 nm

In Fig. 2, for a relatively low F_0 crystalline silicon is also visible in the laser irradiated region. However, for higher fluences, an amorphous area was detected in the center of the laser irradiated area (Fig. 2 middle). The amorphous layer is thicker than approx. 40 nm. In addition, the thickness of the amorphous layer depends on the laser fluence. For the highest fluence, the amorphous layer is thinner than approx. 40 nm in the center of the irradiated area. Further, a color gradient appears in the light microscope image (Fig. 2 left). Thereby, the color depends on the thickness of a dielectric layer. These results are hints that this amorphous layer is partially removed SiN_x.

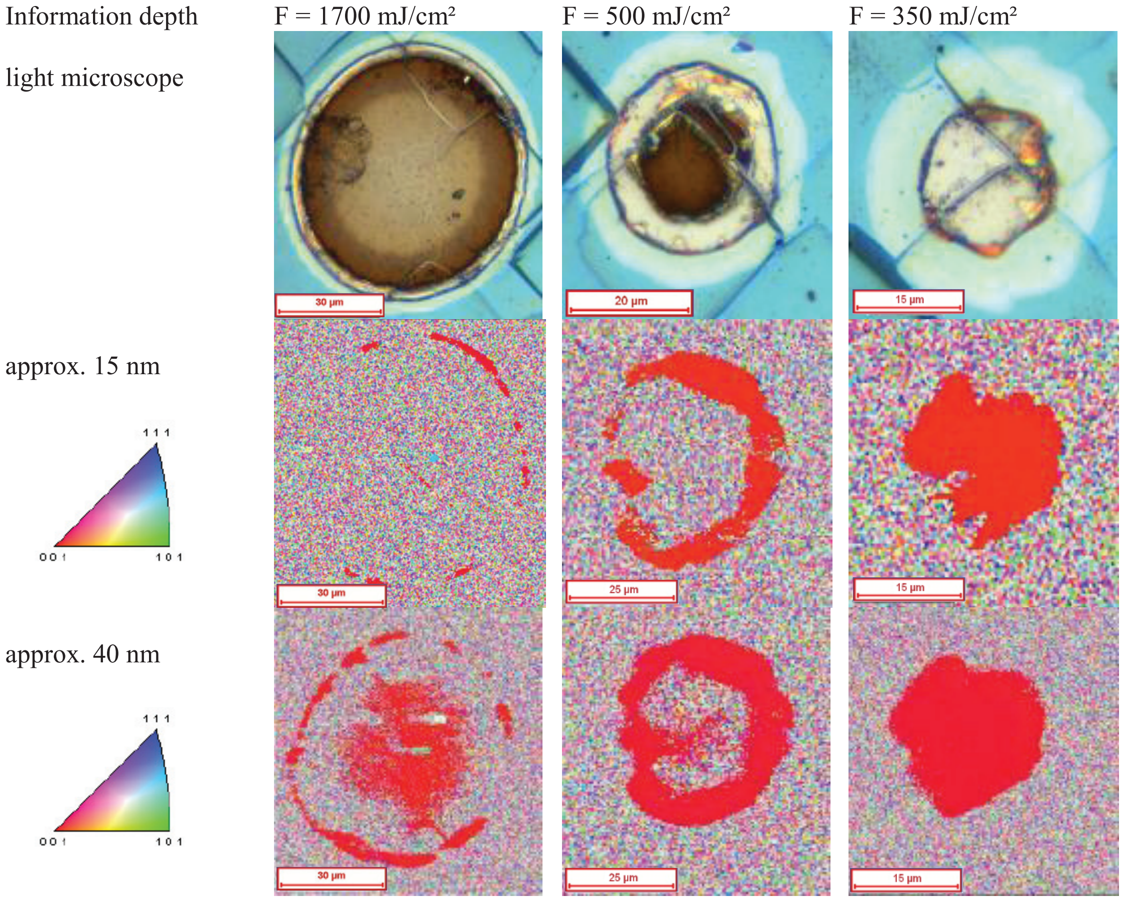


Fig. 2. EBSD and light microscope images after laser irradiation of a SiN_x layer (n=2.1) with several fluences

In addition, AFM measurements on polished samples show that 30 - 50 nm in the laser irradiated center are not removed. The rough surface in the laser irradiated center stems from cracks in the SiN_x (see [7]). However, at the border, the SiN_x is partially bulged and partially completely removed. (see Fig. 3).

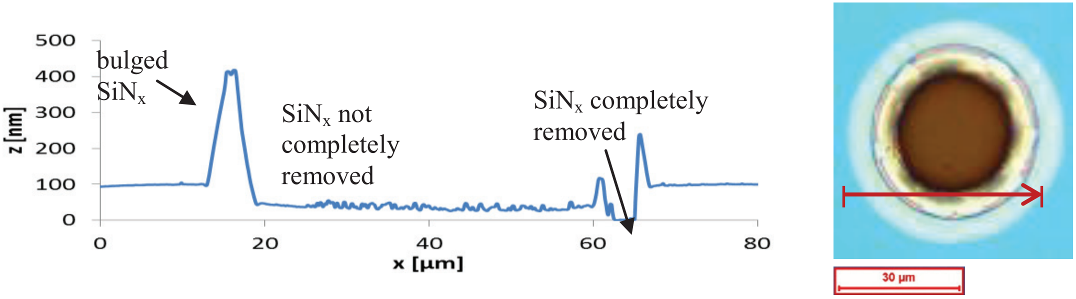


Fig. 3. Atom-force microscope line scan of a laser irradiated area (F_0 = 1000 mJ/cm²) on a polished sample (light microscope image right with line scan for AFM) with SiN_x (n=2.1)

3. Ablation process

In section 2, we can conclude that the amorphous layer for the sample with a high refraction index is partially-removed SiN_x. The SiN_x layer has to absorb the laser pulse energy. However, the measured linear absorption coefficient α_1 is zero 1/cm at 532 nm (see Fig. 4). Hence, the appearance of absorption can be explained by the *two*-photon absorption [8]. *Two* photons (with a total energy of 4.6 eV) suffice, because the determined band gap energy of SiN_x (n=2.1) is 2.7 eV. The depth x dependent *two*-photon absorption is given by

$$\frac{dF(x)}{dx} + \alpha_1 F(x) + \alpha_2 \left(\frac{2}{\tau_p} \sqrt{\frac{\ln(2)}{\pi}} \right) F^2(x) = 0 \tag{1}$$

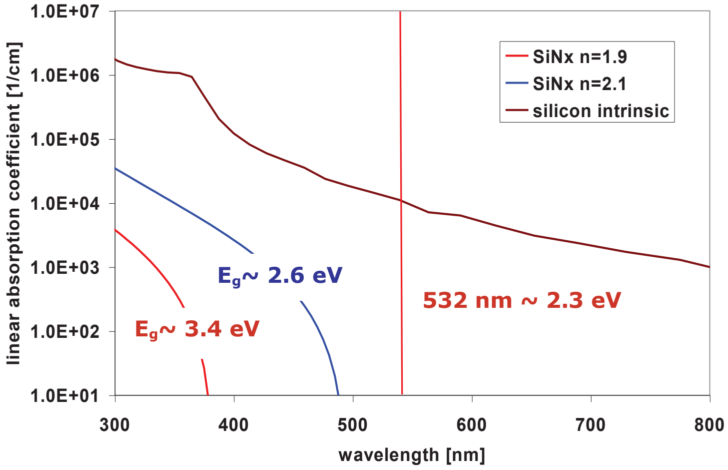


Fig. 4. linear absorption coefficient for two different silicon nitride layers (determined by spectral ellipsometry and using model GenOsc and MSA) and intrinsic silicon [4] as function of incident wavelength

This absorption depends on the fluence F and the pulse duration τ_p of the incident laser pulse and in this case, it is valid for both: silicon nitride and silicon. In our interpretation, the ablation process starts for both samples (n = 1.9 and at low fluences for n = 2.1) with absorption of the pulse energy by the silicon. The SiN_x is transparent. The pulse energy heats up (ΔT) a thin silicon volume dV to evaporation temperature by passing the melting heat E_m (c_p: specific heat capacity; ρ: density)

$$\frac{dQ}{dV} = \rho_{Si} c_{p\_Si} \Delta T + E_{m\_Si} = -\frac{dF(x)}{dx} \tag{2}$$

The generated vapor bulges the above laying SiN_x. If the vapor pressure is high enough, the SiN_x layer is removed by lift-off (indirect ablation, see Fig. 5 left). For the second sample, with higher refraction index, the SiN_x absorbs at higher fluences. Therefore, the bulge of evaporated silicon is only generated at the border of the laser influenced area at low fluences. There, the SiN_x is partially removed by lift-off (see

Fig. 2 left and middle as well as Fig. 5 right). In the center of the laser irradiated area, SiN_x absorbs the laser energy. The pulse energy that reaches silicon is too low to evaporate it (but to melt it?). Therefore, the SiN_x can not be removed by lift-off. But it is removed by direct ablation. Due to non-complete removal of SiN_x, a color gradient appears. Thereby, a brown color indicates a layer thickness of approx. 50 nm. This is confirmed with the AFM line scan (see Fig. 3). Thus, 50 nm of the SiN_x have to be ablated directly by heating up SiN_x to the sublimation temperature of 1900°C [9].

$$\Delta T(x) = \frac{\alpha_{2\_SiNx2.1}}{c_{p\_SiNx}\rho_{SiNx}} \left(\frac{2}{\tau_p} \sqrt{\frac{\ln(2)}{\pi}} \right) \cdot \left[\left(\frac{\tau_p}{2} \sqrt{\frac{\pi}{\ln(2)}} \right)^{-1} \alpha_{2\_SiNx2.1} x + F_0^{-1} \right]^{-2} \tag{3}$$

To estimate the *two*-photon-absorption coefficient of this SiN_x, we assume that $\rho = 3.5$ g cm^{-3} [8] and $c_p = 0.7$ J/(g K) [8] are temperature independent. Therefore, we estimate α_2 by solving eq. (3) with $F_0 = 500$ mJ/cm² to be $2 \cdot 10^5$ cm/TW. For comparison, this value is one order of magnitude higher than the *two*-photon-absorption coefficient of silicon which was determined by *Reitze et al.* [10].

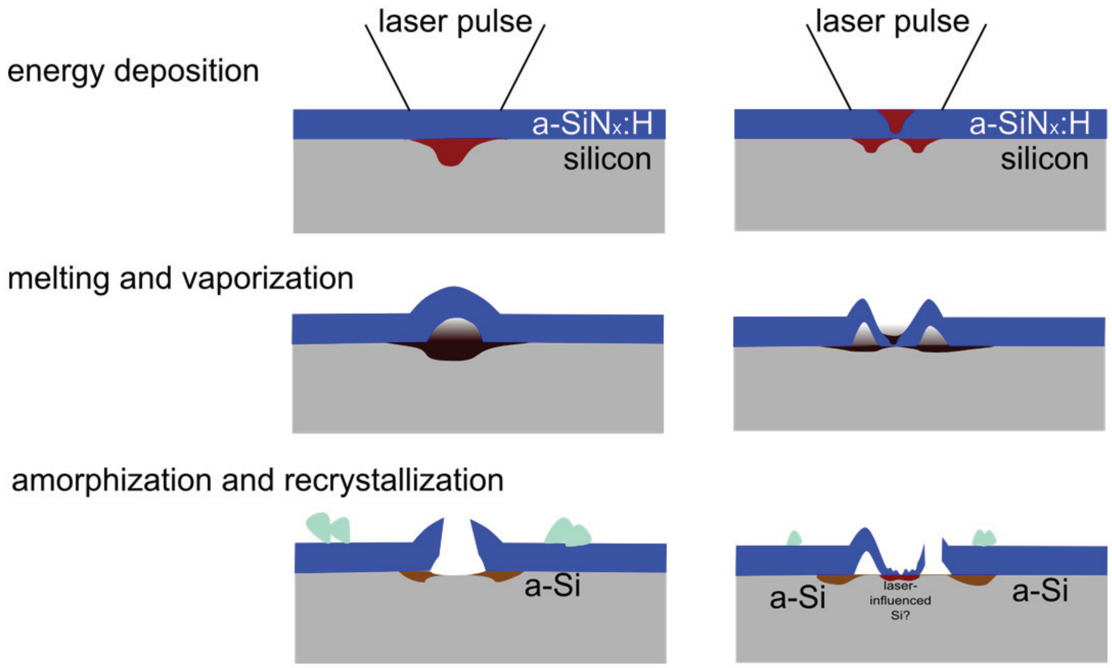


Fig. 5. Laser ablation of dielectrics by indirect ablation (left) and partial lift-off (right); generation of a-Si below SiN_x due to fast cooling down of very small molten silicon volume

4. Summary

In this work, two silicon nitride layers (variation of the silane-to-ammonia ratio), deposited on polished or damage-etched silicon were locally irradiated by ultra short laser pulses. The irradiated areas were investigated by electron backscatter diffraction (EBSD) in order to analyze the near-surface crystallographic orientation and crystallinity.

In this work an indirect ablation is observed for SiN_x (n = 1.9). Further, a change from an indirect ablation to a partial lift-off for SiN_x (n = 2.1) is determined to be fluence dependent. At low fluences, the SiN_x was completely removed. However, at higher fluences, the SiN_x is not completely removed, due to direct ablation. Thereby, the two-photon-absorption coefficient of this SiN_x (n = 2.1) is estimated to be $2 \cdot 10^5$ cm/TW.

Further work will include investigations to the regions where the SiN_x layer is not completely removed. Questions such as: Is there a change in the structure of the SiN_x layer, is there a laser-induced damage in the silicon and, is there an influence on a subsequently metal contact formation, have to be answered.

Acknowledgements

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References

[1] A. Knorz, M. Peters, A. Grohe, C. Harmel, R. Preu, "Selective Laser Ablation of SiNx Layers on Textured Surfaces for Low Temperature Front Side Metallization", Prog. Photovolt. Res. appl. 17:127 (2009)

[2] S. Hermann, T. Dezhdar, N. P. Harder, R. Brendel, M. Seibt, "Impact of surface topography and laser pulse duration for laser ablation of solar cell front side passivating SiNx layers", J. Appl. Phys. 108, 114514 (2010)

[3] T. Rublack, S. Hartnauer, P. Kappe, C. Swiatkowski, G. Seifert, "Selective ablation of thin SiO2 layers on silicon substrates by femto- and picosecond laser pulses", Appl Phys A 103: 43–50 (2011)

[4] V. Juzumas, J. Janusonis, V. Janusoniene, K. Sulinskas, D. Andrijauskas, L. Jaramine, T. Lukstaraupis, D. Janusonis, "selective removal of SiNx by ultrashort laser pulses and nickel silicide formation", Proceedings of 26th EU PVSEC 2011 Hamburg p. 1757 (2011)

[5] T. Rublack, G. Seifert, "Femtosecond laser delamination of thin transparent layers from semiconducting substrates", OPTICAL MATERIALS EXPRESS Vol. 1, No. 4 pp. 543-550 (2011)

[6] D. DINGLEY, "Progressive steps in the development of electron backscatter diffraction and orientation imaging microscopy" Journal of Microscopy, Vol. 213, Pt 3 March 2004, pp. 214–224 (2003)

[7] will be published in G. Heinrich et al, proceedings of E-MRS 2012 Strasbourg

[8] D. Bäuerle, "Laser Processing and Chemistry" (3rd edition, Springer Verlag, 2000)

[9] D.R. Lide, "Handbook of chemistry and physics" (85th edition, CRC Press, 2004-2005) [2] Strunk Jr W, White EB. *The elements of style*. 3rd ed. New York: Macmillan; 1979.

[10] D.H. Reitze, T.R. Zhang, Wm.M. Wood, M.C. Downer, "Two-photon spectroscopy of silicon using femtosecond pulses at above-gap frequencies", J. Opt. Soc. Am. B7, 84 (1990)