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Correlation of stress in silicon nitride layers with their complete removal by laser ablation

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Abstract

In recent years laser ablation of dielectric layers for local structuring of solar cell passivation layers has become more and more common. Apart from adjusting laser parameters for a damage-free removal of dielectric layers, it is necessary to prepare the surface in a way suitable for the respective contact methods (screen printing, nickel plating, etc.). In this study, we demonstrate for silicon nitride layers how the deposition parameters and deposition method correlate to the characteristics of the ablated area. Furthermore a simple method to predict these characteristics is introduced based on the determination of the intrinsic stress in the dielectric layer. A correlation between compressively stressed or stress-free silicon nitride layers and a complete ablation was found.

Keywords: ablation; laser; stress; silicon nitride

1. Introduction

Depending on the desired method of contact formation (e.g. plating) the dielectric passivation layer needs to be completely ablated. Microscopic and energy dispersive X-ray (EDX) studies of the authors have shown different characteristics of the ablated area ranging from complete removal to partially removed layers as well as completely intact dielectric layers. Similar findings were reported by Wütherich et al. [1]. The idea is to find a fundamental connection between the dielectric properties and the ablation

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characteristics. Given that the dominating physical process is indirect ablation (due to the ps pulse range of the laser used for ablation and the properties of the transparent dielectric investigated [2]), a mechanical quantity could be a way to explain the ablation characteristics of the dielectric layer. Considering the pressure of the plasma generated by the laser pulse in the affected area [3] we hypothesise a dependency of the ablation characteristics on the intrinsic stress of the dielectric layer. The stress largely depends on the parameters and method of the silicon nitride deposition [4]. Therefore, the intrinsic stress in the dielectric layer could be a means of optimizing dielectric layers for ablation.

2. Theoretical

2.1. Laser ablation

The ablation of dielectric layers from silicon substrates can be divided in two subcategories; the silicon nitride layers are either directly or indirectly ablatable. Dielectrics are directly ablated if the energy of the laser pulse is absorbed mainly in the layer itself. In case of a Gauss-shaped laser beam the result is a gradual variation of the layer thickness, visible in a continuous sequence of multi-coloured rings surrounding the completely ablated area. Direct ablation therefore depends on optical properties of the dielectric layer (i.e. linear and non-linear absorption). If the absorption coefficient is, however, too low and the dielectric therefore transparent at the relevant wavelength the laser pulse energy is absorbed in the silicon substrate (Fig. 1). The generated plasma at the silicon-dielectric interface builds up pressure. If the absorbed energy exceeds the ablation threshold fluence the plasma breaks the dielectric layer resulting in an ablated area with a sharp edge of the surrounding dielectric film. The indirect ablation therefore depends on the mechanical properties of the dielectric layer (i.e. intrinsic stress).

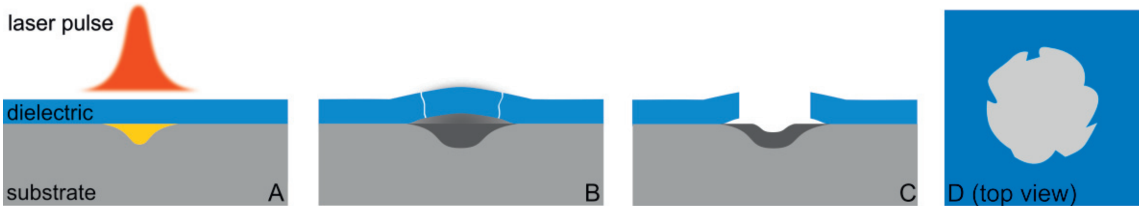

Fig. 1. Schematic indirect laser ablation: (A) laser pulse (red) is absorbed (yellow) in substrate (B) Generation of plasma on the interface and pressure build up (C) Opened silicon nitride layer with sharp edge (D) Topview of ablated area (C) with splintered edges characteristically for indirect ablation

2.2. Intrinsic stress

Plasma-enhanced chemical vapor deposition (PECVD) of silicon nitride layers is generally performed around 400°C. The silicon substrate and the silicon nitride layer are at a thermal equilibrium during the deposition process. The expansion of this compound while cooling down to room temperature depends on the thermal expansion coefficients of the silicon and silicon nitride. A difference in these coefficient values results in a bow of the compound (bimetal effect). Two types of intrinsic stresses in silicon nitrides can be distinguished (Fig. 2). While tensile stress originates from an upward bow compressive stress originates from a downward bow. Microscopically, compressive stress tends to lift the silicon nitride from the interface resulting in blistering. Tensile stress can form micro-cracks and lead to local partial lift up of the layer. [4]

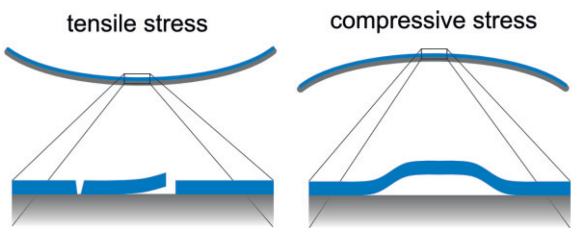

Fig. 2. Left: tensile stress resulting from upward bow with tendency to exhibit micro-cracks; Right: compressive stress resulting from downward bow with tendency to exhibit blisters

The intrinsic stress can be determined by measuring the curvature *k(r)* before and after the deposition of the dielectric (Fig. 3). The only information necessary about the dielectric layer (*L*) is the thickness d_L, making this method a simple way to determine the stress. Furthermore, the thickness d_S, Young's modulus ε_S and Poisson's ratio υ_S of the silicon substrate (*S*) are necessary to determine the intrinsic stress using equation (1) [5].

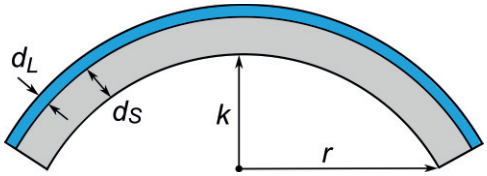

Fig. 3. Curvature measurement parameters: dielectric layer thickness d_L, substrate thickness d_S, curvature k and distance r

$$\sigma = \frac{\varepsilon_S}{1-\nu_S} \cdot \frac{d_S^2}{d_L} \cdot \frac{k}{3r^2} \tag{1}$$

3. Experimental

The circular 6" FZ-Si and damage-etched Cz-Si wafers were coated with silicon nitride in three different PECVD sources. The two direct plasma PECVD sources use a low (40 kHz; D1) or high plasma frequency (13.56 MHz; D2) respectively. The third source is a remote PECVD reactor where the plasma generation and the deposition chamber are separated. To investigate the influence on the ablation and intrinsic stress the deposited silicon nitride layer thickness was varied. To ablate a dot-array with different laser parameters we used a 12 ps pulsed laser source with wavelengths 355 nm and 532 nm. To vary the fluence either the output power or the distance laser focus- wafer surface was adjusted.

Before and after silicon nitride deposition the bow of the Si-wafer was measured and the intrinsic stress was calculated using equation (1). Several wafers of each group of silicon nitrides D1, D2 and R were treated by a high temperature step (firing in belt furnace) before measuring the bow. All wafers then were ablated using different laser parameters. To verify the completeness of the layer removal scanning electron microscopy (SEM), energy dispersive X-ray (EDX) and electron backscatter diffraction (EBSD) measurements were performed.

4. Results and discussion

The results (Fig. 4) show a correlation between the possibility of complete removal by laser ablation and the intrinsic stress of the silicon nitride layer. A wafer coated with silicon nitride D1 displays compressive stress and a complete removal of the dielectric layer for any laser parameter set above the ablation threshold. SEM and optical microscopy measurements show a distinctive sharp edge between the surrounding silicon nitride layer and the ablated area where the silicon substrate is visible. The sharp edges and the absence of a multi-coloured ring pattern suggest an indirect ablation of the dielectric. The same conclusion can be drawn for the edge of the ablated area of the silicon nitrides D2 and R. However, the centre of the laser treated area seems to show remnants of the dielectric layer. EDX and EBSD measurements indicate an amorphous and nitrogen-rich layer that remains in the centre (Fig. 5). Therefore, the silicon nitride layers with tensile stress (D2 and R) could not be ablated completely. The attempt to relieve the dielectric of the intrinsic stress by a high temperature step was not successful. Although the amount of stress was reduced, the type of stress and its influence on the ablation result remained the same. To further verify the correlation between the intrinsic stress and the complete removal of the dielectric layer the deposition parameters for the silicon nitride D2 were changed in order to attain a stress-free dielectric layer. The ablation results were similar to the ablation of silicon nitride D1 with a complete removal of the silicon nitride layer.

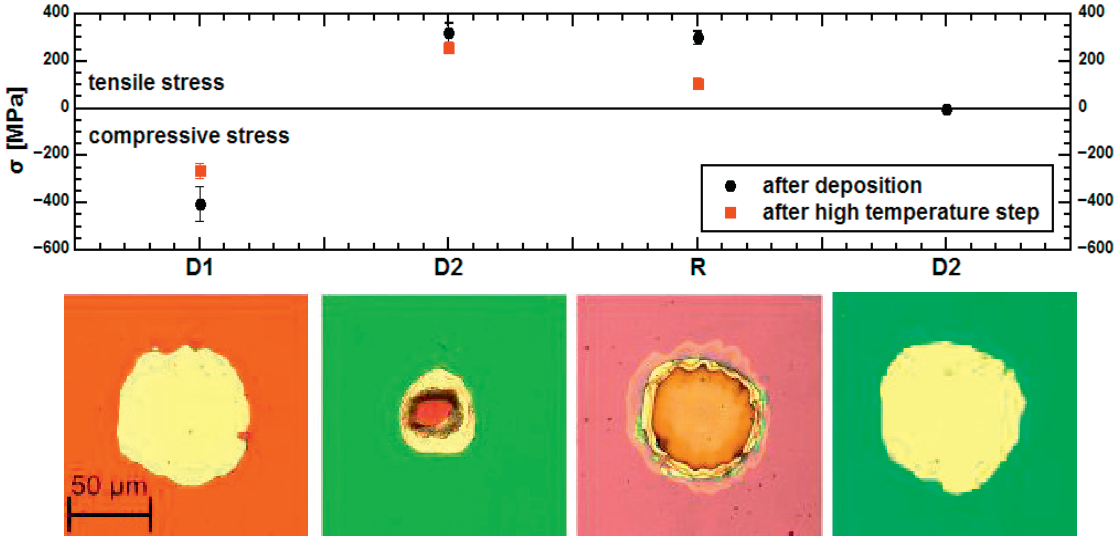

Fig. 4. Intrinsic stress σ and respective microscopy pictures after single laser pulse treatment for all silicon nitride layers D1, D2 and R. Changing the PECVD deposition parameters for D2 leads to a stress-free dielectric layer (far right)

The measurements of the intrinsic stress and the ablation result suggest that for an indirect ablation mechanism stress-free or compressively stressed silicon nitride layers are necessary for a complete removal of the dielectric layer. The mechanical rather than the optical properties of silicon nitride are important due to the nature of the indirect ablation. If the built up pressure resulting from plasma formation on the surface of the silicon substrate underneath the dielectric layer is sufficient, the dielectric layer can be ablated. A compressive stress assists this process by destabilizing the silicon-dielectric interface. Tensile stress in contrast might prevent a pressure being built up due to micro-cracks. The microscopic processes leading to the incomplete ablation for tensile stressed layers during the ablation process are not yet investigated.

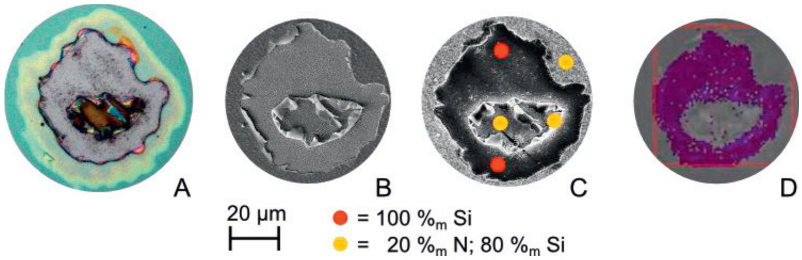

Fig. 5 (A) Optical microscopy image of ablated area (silicon nitride R) (B) SEM topography image (C) SEM material contrast image with EDX measurement points (red and yellow) (D) EBSD image showing crystalline Si areas in purple

The intrinsic stress depends on the deposition parameters and has three main origins: plasma chemistry, microstructure of the layer and particle bombardment during deposition [4]. Remote PECVD sources for example produce rather tensile stressed layers due to the lack of direct particle bombardment [6]. Therefore direct plasma sources deposit mainly compressively stressed silicon nitride. The possibility to change the deposition parameters and the resulting intrinsic stress can be used to optimize the dielectric layer to be completely removable by laser ablation. The measurements showed a quantitative dependency of the intrinsic stress on the deposition parameters. Hence it is advantageous to monitor the intrinsic stress rather than the ablation result while varying the deposition parameters. A respectively optimized silicon nitride layer can be completely removed with a larger range of laser parameters to attain the desired ablation result. Given the sufficient number of deposition parameters it is possible to change the intrinsic stress and retain the desired optical properties (i.e. antireflective coating ARC).

5. Conclusion

A correlation between the intrinsic stress in silicon nitride layers and the possibility of a complete removal by laser ablation was demonstrated. Due to the nature of the indirect ablation a compressively stressed or stress-free dielectric layer proved to be necessary to be removed completely. Tensile stress in silicon nitride results in a partially ablated dielectric layer with a silicon nitride film remaining in the centre of the laser treated area. Furthermore a procedure to optimize the dielectric layer for laser ablation by varying the PECVD deposition parameters was proposed.

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