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Bias-plasma assisted RF magnetron sputter deposition of hydrogen-less amorphous silicon

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Abstract

The execution of special hydrogen diffusion experiments requires an initially hydrogen-free drain layer. Hydrogen-free amorphous silicon (a-Si) deposited by radio frequency magnetron sputter deposition (RFSD) serves this purpose. RFSD yields a rough surface of the film but this can be flattened by an additional post-hydrogenation step. Weak Si-Si bonds are reorganized by hydrogen and the surface becomes smoother. However, by post-hydrogenation the a-Si layer loses its hydrogen-free characteristic. Bias-plasma assisted RFSD offers the possibility of a direct deposition of hydrogen-free a-Si films that exhibit a smooth surface. In this way an amorphous network with only few vacancies and related defects can be achieved as a consequence of the reorganization of weak Si-Si bonds during bias-plasma assisted deposition. Using a crystalline silicon wafer as base substrate for deposition the bias-plasma can additionally be used to prepare the c-Si surface whereby the HF-dip for removing native oxide can be omitted. The optimal deposition temperature of RFSD without bias-plasma, with respect to surface passivation, is ~325°C. Bias-plasma assisted RFSD leads to an additional interaction of atoms on the surface of the growing a-Si layer with atoms in the bias-plasma. This interaction decreases the optimal deposition temperature to ~275°C. Furthermore, the bias-plasma related flattening of the a-Si surface yields higher passivation quality of post-hydrogenated thin layers (≤ 40 nm) while the formation of additional ion induced defects decreases the passivation quality of thick (>> 40 nm) a-Si layers.

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1. Introduction

Radio frequency magnetron sputter deposition (RFSD) offers the possibility to deposit hydrogen-free amorphous silicon (a-Si) on crystalline silicon (c-Si). The RFSD technology uses a solid target consisting solely of the material intended to be deposited whereby deposition of hydrogen-free a-Si becomes possible [1].

Hydrogen-less a-Si layers could be used as a drain layer for advanced hydrogen diffusion experiments [2]. Furthermore, analyzing formerly hydrogen-less a-Si during a post-hydrogenation step allows determining hydrogen related influences on electrical, optical and structural characteristics [3]. As discussed in Ref. [3], the investigation of the progress of hydrogen based saturation of defects like dangling bonds and the related reduction of surface recombination velocity with post-hydrogenation duration can be evaluated by effective minority carrier lifetime measurements (τ_{eff}).

Compared to parallel-plate plasma-enhanced chemical vapor deposition (PECVD) there is not a direct plasma contact of the sample in the RFSD reactor whereby a plasma induced reorganization of weak Si-Si bonds during deposition is missing. Therefore a higher optimal deposition temperature with respect to surface passivation is needed. While several publications have shown that an optimal deposition temperature of PECV-deposition is at ~250°C, the optimal deposition temperature of RFS-deposited a-Si is ~325°C [3-7].

Bias-plasma assisted RFSD (BPA-RFSD) uses a second plasma directly above the sample leading to a smooth surface of the a-Si layer. This effect is probably based on the mentioned plasma induced reorganization of weak Si-Si bonds. This paper points out the advantages of the bias-plasma induced reorganization of weak Si-Si bonds already during deposition. Changes in the structural characteristics of deposited films will also be investigated as changes in the electrical characteristic after a post-hydrogenation step.

An application for BPA-RFS-deposition is the preparation of hydrogen drain layers for hydrogen diffusion and effusion experiments. As discussed in Ref. [3] for such experiments it is desirable to work with hydrogen-less amorphous layers with a very smooth surface to reduce misinterpretations at the (i) a-Si surface while measuring and analyzing hydrogen depth profiles.

2. Sample preparation and experimental conditions

The here investigated intrinsic (i) a-Si layers are RFS-deposited at a pressure of 2 mTorr using only Ar as process gas. Bias-plasma assisted as well as standard RFS-deposition takes place in an "AJA ATC 2200" RF magnetron sputtering system. For the experiments phosphorous doped (n-type) chemically polished float-zone (FZ) silicon wafers (c-Si) are used (5 Ωcm, 250 µm <100> oriented). If necessary, native oxide at the surface of the c-Si wafers is chemically removed in diluted hydrogen fluoride solution (HF) directly before RFS-deposition [3].

Surface roughness of RFS-deposited (i) a-Si layers are analyzed by atomic force microscopy (AFM) [8]. AFM analyses are carried out using an "Asylum Research MFP-3D" in non-contact mode by scanning an (1 × 1) µm^2 area with 2^{16} points (256 × 256).

Several samples are deposited with or without bias-plasma by varying layer thickness as well as deposition temperature. The samples are post-hydrogenated using a MIRHP (microwave-induced remote hydrogen plasma) reactor at a temperature of 370°C [9]. According to Ref. [3] the duration of the post-hydrogenation step depends on the thickness of the amorphous layer. All here investigated layers are post-hydrogenated for 100 min/nm [3]. During post-hydrogenation hydrogen accumulates in the RFSD (i) a-Si, saturates defects like dangling bonds and yields finally surface passivation of the c-Si. Comparing τ_{eff} of post-hydrogenated (i) a-Si (standard and bias-plasma assisted RFSD) allows investigating the influence of bias-plasma during the deposition process. The values of τ_{eff} itself are measured by transient and quasi-steady-state photo conductance decay at ~25°C (WCT 120, Sinton Instruments) [10].

3. Surface roughness

The topography of hydrogen-less RFS-deposited a-Si becomes highly uneven while the surface roughness is also high (Fig. 1, a) [3]. The statistical evaluation of the standard deviation of surface roughness (R_q) (Ref. [11]) is shown

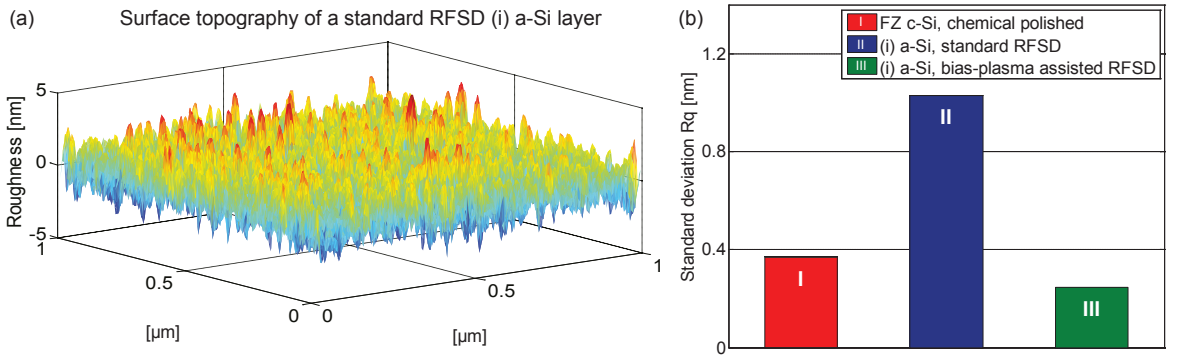

Fig. 1. (a) AFM measured surface topography of a 115 nm thick standard RFSD-deposited (i) a-Si layer; (b) comparison of the standard deviation of the surface roughness calculated from surface topography.

in Fig. 1 (b). In more detail, the bar graph compares R_q of a standard RFS-deposited (i) a-Si layer and a bias-plasma assisted RFS-deposited (i) a-Si layer with a chemical etched FZ c-Si wafer.

The bar graph in Fig. 1 (b) shows that, R_q of a standard RFSD (i) a-Si layer is ~1 nm. It can be assumed that due to the missing direct plasma contact the surface of the (i) a-Si becomes rougher during standard RFS-deposition compared to BPA-RFSD.

The roughness, calculated (Fig. 1, b) from the AFM measured surface topography (Fig. 1, a), is higher than for the chemical polished FZ c-Si reference material (R_q = 0.4 nm).

As shown in Fig. 1 (b) the standard deviation of a BPA-RFS-deposited (i) a-Si layer is about 0.25 nm and even lower than for the chemical polished FZ c-Si reference. BPA-RFSD provides direct contact of the growing (i) a-Si surface with a plasma leading to a smooth surface. It can be supposed that the smoothening of the surface occur by breaking up weak Si-Si bonds as well as disintegrating Si structures sticking out of the surface.

As mentioned in Ref. [3] the surface roughness of standard deposited RFSD (i) a-Si becomes lower during an additional post-hydrogenation step using remote hydrogen plasma and a reduction of R_q of ~20% is achieved (~1 nm → ~0.8 nm). Whereas this is a significant reduction of the surface roughness, R_q of an BPA-RFS-deposited (i) a-Si layer this is still lower.

4. Plasma induced surface preparation

The abrasive process of BPA-RFS-deposition smoothening the surface of the growing (i) a-Si layer can be used for surface preparation prior to deposition. The HF-dip for removing native oxide can be omitted if the bias-plasma is ignited prior to the main-plasma. During this first period of the process the bias-plasma sputters the surface of the c-Si sample and removes the native oxide.

As can be seen in Fig. 2 (a, ♦) the combination of BPA-RFSD and HF-dip yields a low surface passivation quality of post-hydrogenated samples ($\leq$ 50 µs) indicating a high concentration of defects at the (i) a-Si/c-Si interface. These interface defects are a consequence of the mentioned abrasive effect of the bias-plasma [3]. Therefore, there is an optimum time period between ignition of the bias-plasma to remove the native oxide and the ignition of the main-plasma to cover the c-Si with (i) a-Si and to "protect" the surface of the c-Si sample. The here discussed samples are deposited including a bias-plasma cleaning step of ten seconds.

5. Deposition conditions

5.1. Deposition temperature

As discussed in section 4, the smoothening of the surface during BPA-RFSD can be attributed to a continuous plasma related reorganization of weak Si-Si bonds. Furthermore, in consequence of the ongoing reorganization process a decrease of defects in the (i) a-Si layer can be supposed.

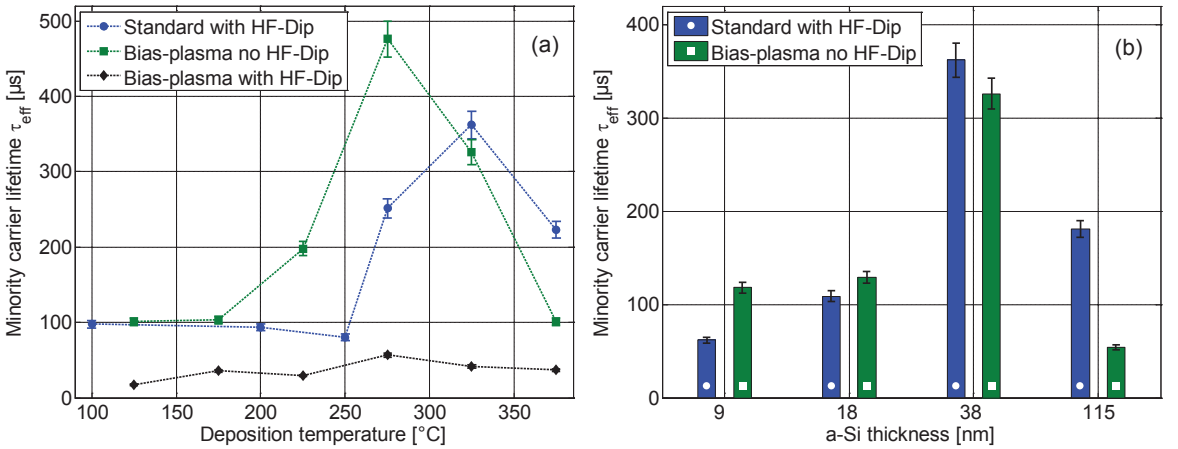

Fig. 2. (a) Minority carrier lifetime (τ_{eff}) of ~40 nm thin (i) a-Si layers RFS-deposited with and without bias-plasma assistance as a function of RFSD temperature as well as comparison of bias-plasma assisted RFSD with and without an additional HF-dip; (b) τ_{eff} of (i) a-Si layers RFS-deposited with varying thicknesses with and without bias-plasma enhancement.

Fig. 2 (a) shows i. a. the evolution of τ_{eff} after the mentioned post-hydrogenation step of (i) a-Si layers, RFS-deposited with (■) and without (●) bias-plasma assistance and as a function of RFS-deposition temperature. The post-hydrogenation itself occur using a hydrogen remote plasma at a temperature of 370°C for a duration of 100 min/nm [3].

The maximum of τ_{eff} for RFSD (●) is ~360 µs while surface passivation quality of BPA-RFS-deposited and post-hydrogenated (i) a-Si rises up to ~480 µs.

With respect to surface passivation several publications have shown that an optimal deposition temperature for a-Si deposited on c-Si wafers by using a direct-plasma reactor like PECVD is~250°C [4-6]. Moreover, several published investigations of RFSD a-Si layers (direct- as well as post-hydrogenated ones) mention an optimal RFS-deposition temperature of ~325°C [3, 7]. The missing interaction of atoms on the surface of the growing a-Si layer with atoms in the plasma seems to drive the optimal process to higher deposition temperatures.

As can be seen in Fig. 2 (a) the optimal deposition temperature, with respect to surface passivation, decreases from 325°C (●) to ~275°C (■) when using BPA-RFSD.

This is slightly higher than the optimal temperature of PECV-deposition of 225°C…250°C [4, 5]. Furthermore these findings support the conclusion of Ref. [3] mentioning that the higher deposition temperature of the RFS-deposition is related to the missing direct plasma contact.

5.2. Layer thickness

Fig. 2 (b) shows the evolution of τ_{eff} for RFSD (i) a-Si layers (deposited at 325°C) with varying thicknesses deposited with (■) and without (●) bias-plasma assistance. As mentioned in literature [3, 7], the optimal layer thickness of RFSD (i) a-Si with respect to the passivation quality is ~40 nm. As can be seen in Fig. 2 (b) the here investigated RFSD as well as BPA-RFSD (i) a-Si layers shows the same behavior and exhibit an optimal layer thickness of ~40 nm. The absolute value of τ_{eff} of BPA-RFSD (■) is lower compared to ● because Fig. 2 (b) compares layers deposited at 325°C.

Furthermore, it can be seen in Fig. 2 (b), that the surface passivation quality of BPA-RFS-deposited thin (i) a-Si layers (■) increases (< 40 nm), compared to RFSD layers (●) of the same thickness. In more detail, τ_{eff} of a ~9 nm thin (i) a-Si layer deposited by RFSD is nearly half of the value of a BPA-RFSD (i) a-Si layer of the same thickness (RFSD: $\tau_{eff} \approx 62$ µs; BPA-RFSD: $\tau_{eff} \approx 118$ µs) whereas τ_{eff} of ~18 nm RFSD (i) a-Si is only ~15% lower than BPA-RFSD (i) a-Si (RFSD: $\tau_{eff} \approx 109$ µs; BPA-RFSD: $\tau_{eff} \approx 129$ µs).

The sputter process itself causes damage to the a-Si bulk as well as to the a-Si/c-Si interface and the c-Si by a high energy photon-induced formation of defects [12]. Using an additional bias-plasma direct in front of the sample

increases the formation of such defects. Due to this, the surface passivation quality of thick BPA-RFS-deposited (i) a-Si layers (▬) decreases significantly compared to RFS-deposited (i) a-Si layers (▬).

6. Conclusions

A bias-plasma assisted RFS-deposition of hydrogen-less (i) a-Si yields several benefits compared to "standard" RFS-deposited layers.

- Smoothening the surface,
- Plasma induced surface conditioning, HF-dip can be omitted,
- Lowering of the optimal deposition temperature (325°C → 275°C),
- Surface passivation quality of thin layers (≤ 40 nm) increases (additional post-hydrogenation necessary).

Beside these positive issues one negative aspect has to be mentioned. Due to the additional bias-plasma the formation of ion (as well as radical) induced defects increases. This leads to a significant decrease of passivation quality for thick (>> 40 nm) BPA-RFSD (i) a-Si layers compared to RFS-deposited ones.

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