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APCVD (N) POLY-SI PASSIVATING CONTACTS ON TEXTURED AND PLANAR SURFACES

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ABSTRACT: Planar and textured APCVD (n) poly-Si/SiO$_x$ passivating contacts with a ~60 nm poly-Si layer were metallized by screen-printing. Higher contact resistivity on textured samples $\rho_{C,textured}$ (~6-7 mΩcm² compared to $\rho_{C,planar}$ ~3 mΩcm²) can be attributed to a thinner poly-Si layer and to a more aggressive etching behaviour of the paste around the pyramid tips. Since this behaviour also occurs in classical contact formation on monocrystalline Si, we conclude that the geometrical structure of the pyramids affects the contact formation more than the structure of the used layers. Passivation quality was measured in the non-metallized region between 2-4 fA/cm^2 for planar samples and to a minimum of 17 fA/cm^2 for textured samples. In the metallized regions, $J_{0,Met}$ increases towards higher firing temperatures from ~20 fA/cm^2 to ~140 fA/cm^2 for planar samples and from 140 fA/cm^2 to 830 fA/cm^2 for textured samples.

1 INTRODUCTION

Passivating contacts, which are based on polycrystalline silicon (poly-Si) and a thin SiO$_x$ layer, enable high efficiencies and are therefore more and more used in the global PV market [1,2]. The very good passivation quality, especially under the metal contacts, is the distinguishing factor compared to previous generations of cell structures, which is caused by a high selectivity [3,4]. In particular, a kind of spatial separation is created between metal contacts and minority charge carriers, which leads to low recombination often expressed as saturation current density ($J_{0,Met}$). For application in high performance passivating contacts with a very thin poly-Si layer, the metallization must satisfy both, a low $J_{0,Met}$ and a low contact resistivity (ρ_C) between the metal finger and the poly-Si layer. Various groups have already achieved very good results in their investigations on the contact formation of (n) poly-Si passivating contacts. Thereby, the required amorphous-Si layer (a-Si) is mostly deposited by low pressure chemical vapor deposition (LPCVD) (e.g., [5,6]) and plasma enhanced chemical vapour deposition (PECVD) (e.g., [7]), which both need a vacuum system and are thus less cost-effective.

In contrast, for the experiments presented here, we deposit a single sided (n) a-Si layer by atmospheric pressure chemical vapour deposition (APCVD). The inline deposition tool from SCHMID GROUP stands out above other deposition techniques by its high throughput since no vacuum system is required and thus enables a cost-effective alternative to the beforementioned techniques [8]. For these APCVD (n) poly-Si/SiO$_x$ passivating contacts, we are investigating the contact formation with non-commercial fire-through Ag pastes on planar and textured surfaces through screen-printing.

2 EXPERIMENTAL

For this work, n-type (4.5 Ωcm), n-type (35 Ωcm), and p-type (1.3 Ωcm), Czochralski grown crystalline silicon (c-Si) substrates with a size of 156x156 mm^2 and a thickness of 180 µm were saw damage etched by potassium hydroxide. n-type 35 Ωcm samples and parts of the p-type c-Si substrates were treated with an alkaline texture before all samples were subsequently exposed to a wet chemical ozone cleaning. Afterwards, a nominal 1.5 nm thick thermal oxide was grown in a classical tube diffusion furnace. For p-type samples, a 64(15) nm thick (n) amorphous-silicon (a-Si) layer was deposited on both sides using the APCVD tool from SCHMID GROUP, which corresponds to 55(15) nm for textured samples. On planar n-type base material samples ~65(5) nm and on textured samples ~60(5) nm (n) a-Si were deposited. The junction formation was performed subsequently in a tube furnace at a temperature of 920°C for 30 minutes. During this step, the a-Si layer was crystallized and in-diffusion of phosphorous through the thermal SiO$_x$ occurred. For hydrogenation, a 75 nm thick SiN$_x$ layer was deposited on the samples using a PECVD system, whereby the deposition conditions for the textured samples were adjusted so that the SiN$_x$ thickness for planar and textured samples were equal. The metallization was carried out by screen-printing with a non-commercial fire-through Ag paste. While for the samples with the p-type substrate transfer length method (TLM) patterns with finger width of 40 µm were printed, on the passivation samples (n-type base substrate) 45 µm fingers with varying finger pitches were printed leading to six 4x4 cm^2 areas with different metallization fraction between 0%-21%.

The subsequent contact formation was achieved by fast firing in a standard belt furnace at five different set peak temperatures. Therefore, the TLM samples were laser cut to a size of 5x5 cm^2, resulting in five samples per group for each set peak firing temperature. Samples for evaluation of passivation were fired in 156x156 cm^2 size, but set peak firing temperatures were lowered to 765°C-865°C.

The contact resistivity (ρ_C) was evaluated by TLM measurement with a pv-tools setup. For a further investigation of the contact formation between the silver paste and the (n) poly-Si layer, the metal finger was removed. This was achieved through etching the bulk Ag finger in a nitric acid solution and etching the glass layer in diluted hydrofluoric acid. The now visible microstructure was then examined by scanning electron microscopy (SEM). In order to characterize the samples with respect to their passivation quality, photoconductance decay (PCD) was measured on non-metallized reference samples using a Sinton lifetime tester. In addition, the saturation current density at Ag metal contacts was determined using a time-resolved photo-luminescence setup. The measurement provides a lifetime map of the single-sided metallized sample for different minority charge carrier densities. In high injection, a J_0 can be extracted for each pixel by a linear fit according to the method of Kane and Swanson [9]. By extrapolating the J_0 for the areas with different metallization fractions to 100%, a $J_{0,Met}$ value can be determined. A detailed explanation and the limitations of this evaluation can be found in Glatthaar et al. [10].

3 RESULTS

In the following, passivation values for APCVD (n) poly-Si passivating contacts are shown first, with a distinction between metallized and non-metallized samples. A contact formation study shows in addition to TLM measurements the contact area between the metal paste and the poly-Si/SiO$_x$ surface after chemical removal of the metal finger.

The results presented below are mostly and also in more detail presented in another publication [10].

3.1 Passivation quality

In Figure 1, the passivation for metallized and non-metallized (n) poly-Si/SiO$_x$ stacks on n-type c-Si substrates is shown in terms of the saturation current density (J_0). For planar samples, very low $J_{0.Pass}$ 2-4 fA/cm^2 can be measured. These are corresponding to an implied open circuit voltage (iV_{OC}) of ~740 mV and demonstrate the high potential for passivation of the APCVD (n) poly-Si/SiO$_x$ junction. While for planar samples the firing temperature does not have a strong impact on the passivation, for textured samples $J_{0,Pass,textured}$ increases from ~20 fA/cm^2 to ~70 fA/cm^2. At this point, it should be noted that for no particular reason the silicon base material has different resistivities for both groups of samples, as well as the (n) poly-Si thickness is not exactly the same (compare therefore Section Experimental).

The passivation under the metallized region of the planar samples shows a $J_{0,Met,planar}$ of ~20 fA/cm^2 at 765°C, increasing to ~140 fA/cm^2 for a set peak firing temperature of 865°C. An increasing firing temperature affects the passivation of textured samples much stronger than planar samples, resulting in an enhancement of $J_{0,Met,textured}$ from ~140 fA/cm^2 to ~830 fA/cm^2.

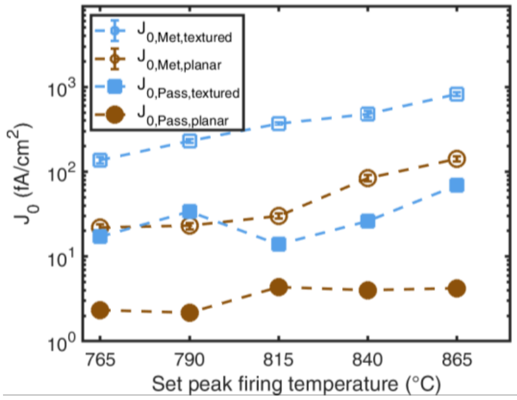

Figure 1: Saturation current density values (J_0) for planar and textured substrates with APCVD (n) poly-Si/SiO$_x$ structures. $J_{0,Pass}$ values were obtained by PCD measurement on symmetrical samples. $J_{0,Met}$ values were obtained by injection-dependent, time-resolved photo-luminescence evaluation on single-sided screen printed samples. Resulting J_0 values for six different metallization fractions allows an extrapolation to the $J_{0,Met}$ at 100% metallization. While each shown data point corresponds to a measurement on one sample, uncertainty is a result of the used analysis. Dashed lines are a guide to the eye. Note the actual sample temperature is in part significantly below the here indicated set peak firing temperature.

3.2 Contact resistivity measurements

In a second experiment on samples with p-type c-Si substrate, the differences in contact resistivity between planar and textured samples will elaborated. Note that, in addition to a different base material, the sample size in the following is 5x5 cm^2, which means that, especially at the fast firing process, the actual sample temperature behaviour can differ significantly to the samples prepared for passivation measurements. Figure 2 shows ρ_C for planar and textured (n) poly-Si/SiO$_x$ structures for set peak firing temperatures of 825-900°C. For samples with planar surfaces, contact resistivity slightly decreases towards higher firing temperatures with a minimum mean value of ρ_C ~3 mΩcm² at 850°C. The textured samples show higher ρ_C of ~6-7 mΩcm², whereby an influence of the firing temperature is not clearly visible. In literature, it is often reported that contact formation is significantly better for textured samples than for planar ones [11]. A part of the observed difference in ρ_C can be explained by the thinner (n) poly-Si layer for textured samples, since the layer thickness has also a large impact on contact formation [5]. However, we expect that this difference in thickness cannot explain that ρ_C for planar and textured samples shows the opposite trend compared to diffused wafer surface without poly-Si.

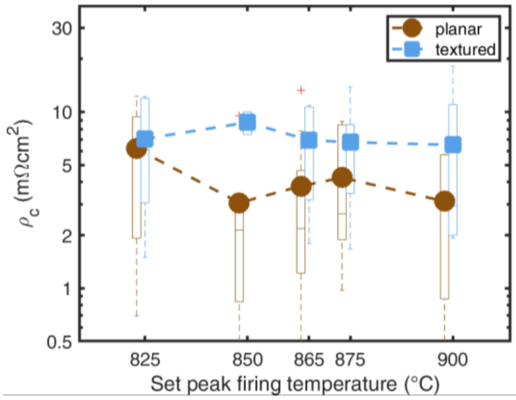

Figure 2: Contact resistivity measurements for planar and textured APCVD (n) poly-Si/SiO$_x$ structures. Measurement points are taken from five different 5x5 cm^2 samples. TLM measurements with 40 µm finger widths are shown. Dashed lines between the mean values are a guide to the eye. Note the actual sample temperature is in part significantly below the here indicated set peak firing temperature.

3.3 Surface analysis

To understand the differences between planar and textured samples in contact formation microscopically, SEM images of the surfaces were taken after the chemical removal of the metallization. Figure 3a shows the surface of a planar (n) poly-Si sample fired at a set peak temperature of 825°C. Although some areas of the sample are still covered with SiN$_x$ (blue colored), most of the sample surface is covered by the poly-Si layer (yellow colored), which is at the surface slightly etched by the Ag paste (not shown here). However, at some places the Ag paste consumed the whole poly-Si layer. After firing these imprints are filled with Ag crystallites. Interestingly, the interface to the c-Si bulk substrate is not damaged (a detailed analysis on that can be found in [10]). Furthermore, at a set peak firing temperature of 900°C, the amount of contact imprints in the poly-Si is increased as can be seen in Figure 3b. However, a clear reduction of the SiN_x covered area is not detected.

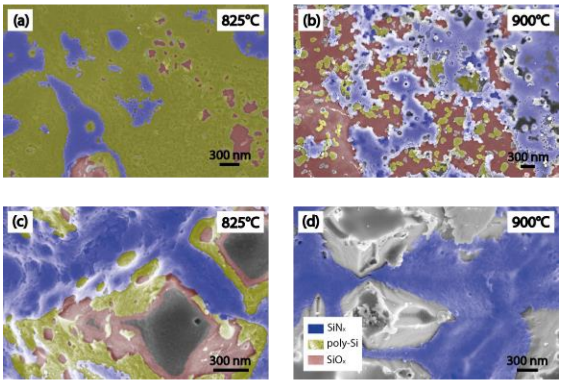

Figure 3: Microstructure after chemical removal of an Ag finger on planar (a,b) and textured (c,d) (n) poly-Si/SiO_x structures by an etching cascade of HNO_3-HF-HNO_3. Samples in (a) and (c) are fired at a set peak firing temperature of 825°C and (b) and (d) at a set peak firing temperature of 900°C. Blue colored areas highlight the remaining SiN_x layer, yellow colored area the (n) poly-Si layer and red colored area the non-penetrated base substrate and thus presumably the SiO_x layer. Non colored areas (here grey) correspond to imprints in the base substrate caused by the massive etching of the Ag-paste.

For textured samples it is, firstly, noticeable that the etching through the SiN_x layer by the Ag paste takes only place around the tips of the pyramids, whereby in the pyramid valleys the SiN_x layer persists. This can be seen in Figure 3c for a firing temperature of 825°C. Secondly, besides the consumption of the poly-Si layer also the c-Si base substrate is etched by the Ag paste. These imprints are predominantly at the pyramid tip and are increased in size significantly towards a set peak firing temperature of 900°C (Figure 3d). At this firing temperature, the entire highly doped poly-Si layer in the SiN_x free areas is consumed by the Ag paste.

As a result, the grown Ag crystallites are in direct contact with the bulk c-Si leading to a high recombination. Furthermore, since the diffusion of dopants from the poly-Si into the c-Si wafer forms only a shallow emitter, locally high contact resistivities are expected for the interface between Ag crystallite and the lowly doped c-Si substrate. Since similar observations of deep imprints where not made for planar samples, this effect might explain that unexpectedly the contact resistivity for textured samples is not lower than for planar ones.

Interestingly, these massive contact imprints at the pyramid tips also exist in the classical contact formation of textured c-Si emitters [12]. In contrast, the stopping of the Ag paste at the thermal SiO_x interface is not known in this respect. We therefore assume that the geometric structure and the exposure of the pyramid tip to the Ag paste have a high impact on the etching behavior of the Ag paste.

4 CONCLUSION

In this work, very good passivation values for unmetallized ~60 nm APCVD (n) poly-Si/SiO_x passivating contacts on planar substrates with 2-4 fA/cm^2 and also good passivation values for unmetallized textured samples with a minimum of 17 fA/cm^2 could be reached. The passivation quality after contact formation of a fire-through Ag paste and the APCVD (n) poly-Si/SiO_x passivating contacts is further quantified by a $J_{0,Met}$ evaluation. Increasing fast firing temperatures enhances $J_{0,Met}$ from ~20 fA/cm^2 to ~140 fA/cm^2 for planar samples and from 140 fA/cm^2 to 830 fA/cm^2 for textured samples.

In a second experiment, contact resistivity was measured for planar sample structures with mean values of ρ_C ~3 mΩcm². For textured samples ρ_C is slightly higher. This can be attributed to a thinner poly-Si layer and to the etching behavior of the paste around the pyramid tips. The contact imprints for textured samples are comparable to standard Ag contact formation in monocrystalline silicon emitters, in contrast to planar samples. Therefore, we assume that the geometrical influence of the sample's topography on contact formation is stronger than that of the stopping mechanism at the poly-Si/SiO_x interface.

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