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Laser treatment to form an effective base contact in a - Si:H/c-Si heterojunction solar cells

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Abstract

In this paper we investigate the p-type a-Si:H/ia-Si:H/p-type c-Si structure, commonly used as base contact in amorphous/crystalline silicon heterojunction solar cell when fabricated on p-type c-Si wafer. Even though the most effective amorphous silicon/crystalline silicon heterostructure is based on n-type c-Si due to higher bulk lifetime, the p-type c-Si still remains the most common and cheaper substrate for silicon based solar cell. In particular we study the effect of localized 532nm pulsed laser treatment at different laser conditions in order to reduce the cell series resistance due to the base contact. In this approach the p-type a-Si:H layer is used as a source of boron dopant. Depending on the thickness of the p-type a-Si:H film, when the laser beam is focused on p-type a-Si:H layer the boron can be transferred into the c-Si base to form an overdoped region and then an effective local Back Surface Field, able to enhance the hole collection at the metal of the base electrode in the p-type c-Si based heterojunction solar cell. The application of a thin Aluminum layer on top of the amorphous silicon to be treated by laser is also concerned. Series resistance of a transverse structure composed by the laser treated p-type a-Si:H/c-Si/opposite surface contacted by InGa is considered to optimize the laser procedure. Values as low as 0.5 Ωcm^2 are obtained when the aluminum layer is adopted.

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*Keywords:*Heterojunction, p-type, laser treatment.

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1. Introduction

Amorphous silicon/crystalline silicon HeteroJunction (HJ) is an attractive technology to achieve high efficiencies in crystalline based solar cells. The main keypoint is the high Voc reachable due to excellent surface passivation of c-Si wafer as obtainable by the amorphous a-Si:H layers deposition [1]. The substrates used for HJ consists of n-type doped silicon wafers, because of the several advantages offered, like the high bulk lifetime and the possibility to easily contact the n-type base with i-a-Si/n-a-Si:H/TCO stacked layers, however the p-type c-Si still remains the most common and cheaper substrate for silicon based solar cell. In this case, the passivation quality has to be strongly effective and the base contact need to be accurately optimized. To this aim, the formation of a CrSi on the p-a-Si layer has demonstrated to be helpful [2], even if this implies the use of chromium and quite thin amorphous film, which could be not advantageous for the c-Si surface passivation purpose [3] and the optical confinement within the thin wafers, where a Bragg Reflecting Mirror can be instead very helpful [4].

Transparent Conductive Oxide (TCO) films are also used as the front electrode, but needs a silver screen printed grid in order to ensure cell Fill Factor. Since heterojunction is fabricated as a sequence of low temperature processes (less than 250°C), a firing process for the metallization is not allowed, as instead commonly used on homojunction solar cells, therefore different screen printable pastes are needed. Specific products as screen printable pastes based on polymer thick film technology, which show good conductivity at low sintering temperatures due to a percolation mechanism [5], are already available on market [6, 7, 8]. However the specific contact resistivity and line conductivity achievable are quite far from values that can lead to high Fill Factor, unless a multiple, or even distributed bus bars are adopted [9]. In any case the use of silver is a cost factor which still limits the downsizing of solar cell cost.

Considering all these issues we investigate the possibility to form an effective back contact for p-c-Si based solar cells heterostructure with the aid of a laser treatment on p-type a-Si:H layer on the cell backside, followed by screen printing of a Silver paste specifically designed to contact p-type a-Si:H. The treatment on a similar structure completed by a thermally evaporated thin Al layer are also investigated.

2. Experimental

P-type doped c-Si wafers cleaned by standard RCA cleaning procedure are used in the experiments. They are entered in a three chamber Plasma Enhanced Chemical Vapour Deposition(PECVD) system for intrinsic/p-type amorphous layers deposition, according to the following parameters: Pressure of 700mTorr, Temperature of 180°C at substrate, 5W at 13.56MHz RF power and silane flow of 40sccm. After 30 seconds deposition, corresponding to 5nm of intrinsic a-Si:H, 6sccm of B_2H_6 are injected, maintaining the glow discharge on, to deposit p-type a-Si:H film. The deposition process time of this last film are chosen to obtain two different thicknesses of 15nm and 45nm. Selected samples are completed by 150nm thick Aluminum layer thermally evaporated.

The laser used in this experiment to perform the overdoping treatment is obtained by a 14W 1064nm ND-YAG laser, duplicated to green wavelength of 532nm by a KTP crystal, with a final incident power selected between 500 and 650mW. We select a repetition rate of 2kHz and speed of 40mm/s, producing traces at 50μm pitch. This technique is useful to locally promote an overdoping of the c-Si wafer using the p-type a-Si:H layer as a source of boron atoms [10]. Treated zones on the wafer are produced, having dimension of 1x10 mm and each other separated by a distance of 2mm. For each zone the laser beam focus is varied moving the focal plane by micrometers step and varying the laser power density on the beam target. In particular the focus variation ΔF of the laser beam, is varied around a reference distance F of 3cm from the substrate, between the extreme conditions of no interaction with substrate and to the wafer scribing. On the opposite side of the wafer an ohmic contact is ensured by InGa eutectic solution [11]. Current-Voltage (J-V) characteristic measurements are performed on this transversal structure to identify the laser process conditions to produce the lowest series resistance Rs value. Once found the best conditions, to further reduce the Rs value and to approach wider area device, a grid shaped pattern of $1cm^2$ with continuous lines distance of 1 mm by laser scan is performed. This pattern is faster to form with respect to a point by point scheme, and produces a grid of low resistance pattern which strongly reduces the Rs value of the backside contact, also because of the high contact area fraction which is between 30 and 40% depending on the width of laser trace, which ranges between 150 and 180μm, determined by the laser focusing. Moreover, in order to produce an equipotential contact, a silver paint or screen printable paste is subsequently applied on the grid. In Table 1 the matrix for the experiment is reported.

Table 1. Samples produced for the laser treatment and laser power adopted in the experiments.

Sample	p a-Si:H	Al	Laser
A	15 nm	-	500 mW
B	45 nm	-	500 mW / 650 mW
C	45 nm	150 nm	500 mW / 650 mW

3. Results

The laser treatment optimization is carried out by means of series resistance values, evaluated on the slope of the J-V characteristic of each sample measured between the laser treated surface and the opposite side of the wafer contacted by InGa. As a reference, the InGa/p-c-Si/InGa structure is used. This structure reports a Rs= 0.072Ωcm^2, therefore the single side series resistance is Rs*=0.036Ωcm^2. On this basis the Rs values measured on laser treated samples are expected to be higher than Rs*.

In the experiment the laser treatments on the two p-a-Si:H layer with different thickness are compared: 15nm (Sample A) and 45nm (Sample B). While the former is the commonly used in HJ device, the latter represents a larger boron dopant source.

3.1. Sample A – 15nm p-type a-Si:H

The green laser power is initially chosen of 500mW in order to avoid damages to the c-Si surface [12] and then, varying the focal distance, the Rs of the p-a-Si:H/i-a-Si:H/p-c-Si/InGa structure is monitored as reported in Fig. 1.

A laser treatment condition able to producean ohmic contact is achieved and a series resistance value of 3.51Ωcm^2 is obtained. Then this optimized condition is applied to a grid shaped design by a laser scan on a 1cm^2 area. Nevertheless, due to the low conductivity of the p-a-Si:H layer, the Rs value results of 7.06Ωcm^2 and the J-V characteristic begins to move away from the linear behavior typical for an ohmic contact. In order to reduce this undesired effect and produce an equipotential contact a layer of silver paint is applied on the grid-shaped laser treated surface, thus increasing the J-V curve slope. Anyway it does not reach a perfect ohmic contact, as evident from Fig. 2. This suggests that thin p-a-Si:H layer could be not a sufficient boron source to produce a good ohmic contact, so thicker p-a-Si:H layer is investigated.

3.2. Sample B –45nm p-type a-Si:H

As for sample A, the laser beam power is kept at 500mW. In this case the higher boron content due to thicker film helps the contact formation between p-type a-Si:H and c-Si wafer. Indeed the ohmic contact is always obtained for any of the explored ΔF, thus resulting in lower Rs values than that of sample A (1.11 Ωcm^2), as illustrated in Fig. 3a. To lower the series resistance, being the p-type a-Si:H layer three times thicker than that in sample A, higher laser power value is investigated, varying the ΔFin the range between -0.4 and +0.4mm. The ohmic contact is effectively formed, even though high Rs values are obtained as shown in Fig. 3b.

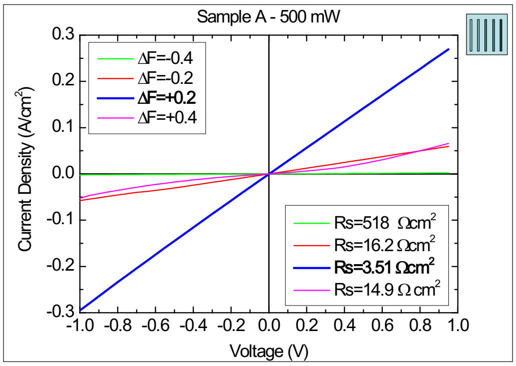

Fig. 1: *J-V characteristics of Sample A treated at different focal distances ΔF. ohmic contact having Rs= 3.51 Ωcm^2 is obtained. The small icon on the top right represents the layout adopted for the laser scan.*

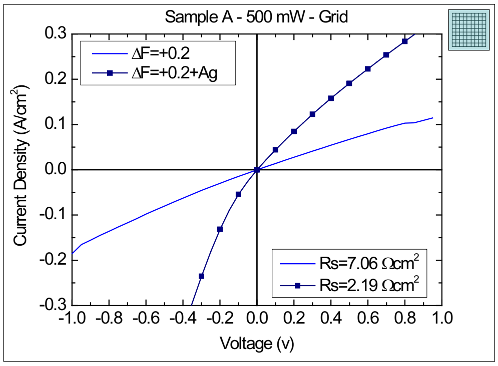

Fig. 2: *J-V characteristics of Sample A treated at the optimized laser beam focus of ΔF=+0.2mm with grid design. The small icon on the top right represents the layout adopted for the laser scan.*

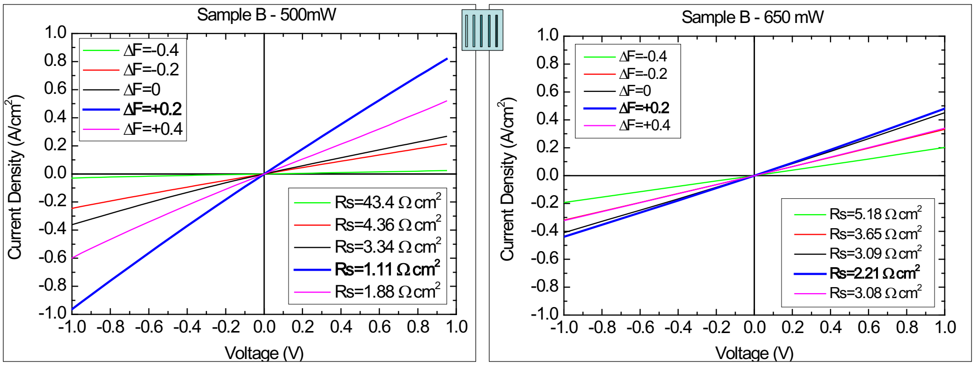

Fig. 3: *J-V characteristics of Sample B treated at 500mW (a) and 650mW (b)of laser beam power for different ΔF values. ohmic contact having Rs as low as 1.11Ωcm^2 has been obtained for samples in Fig. 3a. Fig. 3b shows that higher power of laser beam does not help to reduce the Rs value.*

On the basis of this result, 500mW of laser beam power is used to produce the grid shaped treated surface. As for Sample A, this treatment results in Rs value of 35Ωcm^2 that is higher than the expectation. It is interesting to note in Fig. 4 that both the explored ΔF values, namely ΔF=-0.4mm and +0.2mm, produce the same Rs value as well as J-V curve, as illustrated in Fig. 3a. Subsequent silver paint application reduces the Rs value down to 0.9Ωcm^2, even if a not perfect ohmic contact is obtained yet. Nevertheless this contact is far better than that obtained at 500mW of laser beam power reported in Fig. 2.

3.3. Sample C –45nm p-type a-Si:H + 150nm evaporated Al

The 532nm green laser treatment can be effective to produce an ohmic contact when applied on a structure like p-a-Si:H/i-a-Si:H/p-c-Si, especially when a grid shape design is adopted for the laser scan. The contact can then be completed by a silver layer obtained by a screen printable silver paste, which can be opportunely adapted to fit a p$^+$ doped region [13].

On the other hand, Al is well known to be a dopant for p-type silicon and also it is easy to deposit by thermal evaporation. The laser firing contact [14] is a common technique to produce a point contact promoting the Al diffusion into the c-Si substrate, but needs a 1064nm of wavelength Nd-YAG laser at high power regime. When a 150 nm p-a-Si:H thin layer is adopted, it is still quite transparent to green light, so it can be adopted also in a green laser treatment, being really helpful to produce both a good local overdoping and a metal contact.

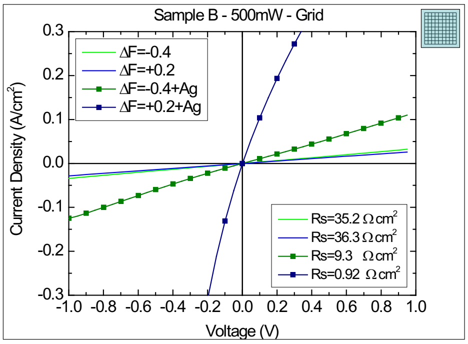

Fig. 4: *J-V Characteristics of Sample B treated at 500mW of laser beam power with a grid shape design of laser scan.*

When the best laser power of 500mW, used for Sample B, is adopted on sample having 45nm thick p-a-Si:H layer and evaporated Al, does not produce an ohmic contact because of poor energy available to promote Al+B diffusion into the c-Si substrate, as illustrated in Fig. 5a. Instead, increasing the laser power to 650mW (Fig. 5b) is then sufficient to ensure a ohmic contact in every focal condition, resulting in a minimum Rs of 2.71Ωcm^2. Performing this last treatment on grid shape laser scan, effective ohmic contact of 0.5Ωcm^2 is finally achieved. In this case silver paint is not further needed, since after its application the J-V curve is nearly the same as before, as shown in Fig. 6.

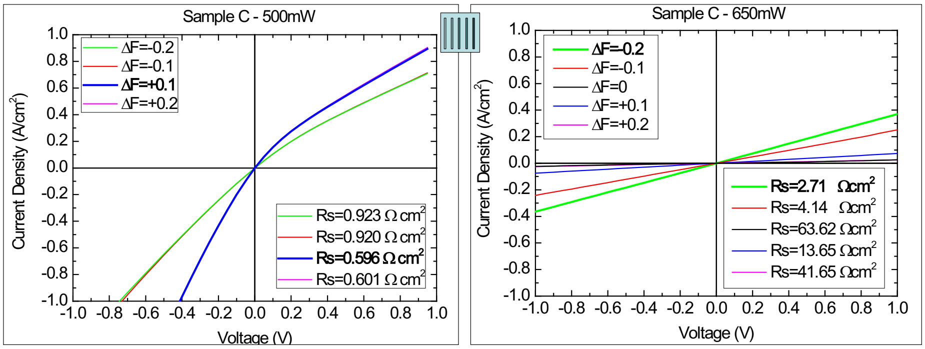

Fig. 5: *J-V characteristics of Sample C treated at 500mW (a) and 650 mW (b) of laser beam power performed at different ΔF of focus beam. ohmic contact is not achieved at 500mW. Instead, at 650mW, ohmic contact as low as 2.71Ωcm^{2}is obtained.*

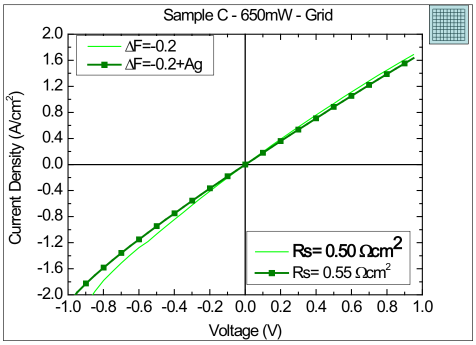

Fig. 6: *J-V characteristics of Sample C treated at 650mW of laser beam power with a grid shape laser scan. The grid design lowers the Rs still maintaining the linearity in the chosen voltage range even when silver is subsequently applied.*

3.4. .Application to heterojuction solar cell and laser point contact

To test the effectiveness of this treatment TCO/n-SiOx/i-a-Si:H/p-c-Si/i-a-Si:H/p-a-Si:H/Al heterostructure solar cells are produced as detailed described elsewhere [15] and the laser treatment at 650 mW of laser beam power with a laser scan to form the grid shape on the back surface, is performed. The width of each laser trace is in this case 180 μm. The cell front electrode has been completed by screen printing a silver grid on TCO layer using a low temperature curing paste. The J-V curve of this sample, measured under class A sunlight simulator in standard AM1.5G and room temperature conditions, is reported in Fig.7. In this case, being the area larger than 1 cm^2, the application on the backside of a thick film of screen printable silver paste enhances the FF up to 78.2%. However a Voc value of 582 mV is measured on this sample. The suns-Voc value measured on the same structure before the laser treatment and metallization reports a Voc value of 695 mV. This large difference in Voc values suggests that the laser treatment, even optimized to produce a good back contact with a relatively low power laser beam regime, damages the back surface passivation, and the grid shaped design, despite the lowering of Rs value, consistently increases the treated area of the contact with respect to the total area of the cell back contact, thus drastically lowering the Voc of the cell. Also the 650 mW laser on the Al covered p-type a-Si:H layer can introduce further issue in the surrounding area of the device because of undesired evaporated and scattered Al particles beside the same laser treatment lines.

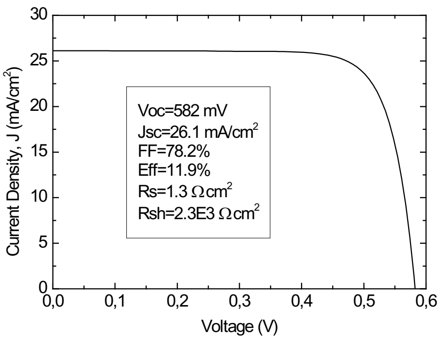

Fig. 7: heterostructure solar cell in which the back contact is produced by a grid shaped laser scan at 500 mW of power beam on the p-a-Si:H layer subsequently covered by screen printed silver layer.

To investigate this issue it is necessary to evaluate the c-Si surface passivation before and after the laser treatment. To this aim p-type c-Si wafer is passivated on both sides by 5nm intrinsic and 45nm p-type a-Si:H, then a laser treatment is performed on one side. Considering the area fraction covered by the grid shaped pattern large enough to induce damages on the surface, a point by point scheme, commonly adopted in laser firing with 1064nm laser, is used in this experiment. 500mW power laser beam at 532nm of wavelength has been used, varying the beam focus distance ΔF to obtain a low and medium laser energy. The effective bulk lifetime τ_{eff} is measured, since it strongly depends on the surface passivation. To compare this experiment with the previous, one side of this symmetric structure is scratched to form an ohmic contact between c-Si substrate and InGa eutectic layer; then theJ-V characteristic of the structure as well as the Rs value is measured. The Rs and $\Delta\tau$, as the difference between the τ_{eff} values measured before and after the laser treatment on the symmetric structure, are listed in Table 2.

The contact area fraction in these cases ranges between 34% and 8%. For both focus conditions of the laser beam, the larger the pitch, the higher the Rs, while the lower intense laser beam produces better contact. Correlating the Rs to the contact area fraction it can be noted that the higher the contact area, the better the Rs value, as evident from Fig. 8. Also it is immediate that the larger pitch introduces higher contribute to the Rs due to the carriers path among the contact points.

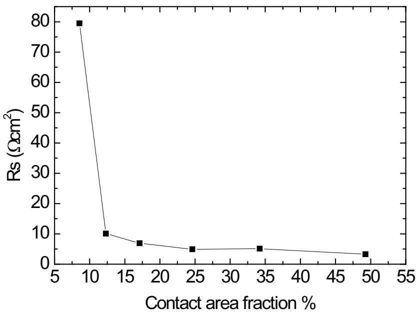

Fig.8: dependence of the Rs on the contact area fraction in a point scheme laser contact. The larger the contact area, the lower the Rs.

When the distance between points is reduced, the influence on lifetime reduction of treated sample with respect to the untreated is more pronounced. In particular higher laser beam power as for ΔF=0.2, produces more damages on the surface passivation thus reducing the lifetime value. On the other hand increasing the pitch distances up to 1 mm do not help to reduce surface damages. From this study it can be stated that the passivation quality and the Rs values work competitively, therefore a careful consideration when applied to the device is strongly required to achieve the best performances.

Table 2: Effect of different point pitch and focus on the τ_{eff} and Rs value for Ag/p-a-Si:H/i-a-Si:H/p-c-Si/i-a-Si:H/InGa structures.

Points pitch (μm)	Low (ΔF=0)	Medium (ΔF=0.2)
250	Δτ =-22%, Rs=3.3 Ωcm^2	Δτ =-55%, Rs=5.1 Ωcm^2
500	Δτ =-11%, Rs=4.9 Ωcm^2	Δτ =-25%, Rs=6.9 Ωcm^2
1000	Δτ=-29%, Rs=10.1 Ωcm^2	Δτ =-17%, Rs=79.5 Ωcm^2

4. Conclusions

In this paper the base contact formation for heterojunction solar cells on p-type c-Si substrates is studied. In particular the use of 532 nm of wavelength laser treatment on a p-a-Si:H/i-a-Si:H/p-c-Si structure is proposed with the aim to use the p-type a-Si:H layer as a source of Boron dopant to overdope the p-type c-Si substrate to form an effective ohmic contact at low temperature useful for heterojunction solar cell application. Rs values of the treated contacts are used to optimize the laser treatment. It is found that 15 nm thick p-type a-Si:H layer is not sufficient as a boron source to produce an effective ohmic contact, while 45nm is sufficient to obtain a linear J-V characteristic for several power density of impinging laser. Particular care is paid on laser power beam during the treatment, indeed a laser power beam as high as 650 mW produces a worst contact with respect to 500mW laser. In both laser power beam regimes, when the laser treatment is performed on a 1cm^2 sample area scanning by a grid with the laser, the contact series resistance Rs can be further lowered by applying a silver layer on top of p-a-Si:H layer. Moreover the introduction of a thin Al layer over the p-a-Si:H layer helps to produce a better contact when a high power laser regime is adopted, resulting in a Rs of 0.5 Ωcm^2. Heterojuntion solar cell fabricated on p-type c-Si substrate and contacted with the optimized laser treatment achieves a FF value of 78.2% but a low Voc value. This effect suggests that when the laser treatment is performed using a grid design laser scan, damages in the back surface passivation of the c-Si substrate occur due to the large treated surface (nearly 40%) with respect to the total device area. To overcome this issue a 500mW laser point contact approach is investigated, also avoiding the use of Al layer, and varying the points pitch and focal plane distance. The obtained Rs values confirm that the passivation level and the contact effectiveness work competitively, both when a grid shaped pattern and a point contact scheme are used, thus requiring a careful consideration in case of application to a solar cell device.

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