18.9% efficient full area laser doped silicon solar cell

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A record in full area laser doped emitter solar cells with an efficiency $\eta=18.9\%$ is reported. Our patented, scanned laser doping process allows for the fabrication of defect free *pn* junctions via liquid state diffusion of predeposited dopant layers in ambient atmosphere without the need of clean room conditions. Our cells display an open circuit voltage $V_{oc}=677$ mV, demonstrating laser doping to be comparable to furnace diffusion. Combining laser diffused *pn* junctions with a textured front side has the potential to boost the short circuit current density J_{sc} and thus the solar cell efficiency η to $\eta>21\%$. © *2009 American Institute of Physics*. [doi:10.1063/1.3232208]

Laser doping (LD) of semiconductors has been known since the 1960s (Ref. 1) with a strong phase of research during the 1980s.[2–4] Just in recent years, LD has come to the attention of photovoltaic industry due to the rapid development of high performance and reliable solid state lasers. The main advantage of LD lies in local selectivity; dopant incorporation only takes place at laser irradiated areas. Using different types of precursors, such as phosphorus or boron, results in *n*-type or *p*-type doped "emitters" in the solar cell's "base".[2,3] LD allows for manifold applications like *in situ* selective emitter formation with highly doped areas underneath the contact fingers and lower doped areas in between. Particularly, for solar cell concepts such as back contacted solar cells, LD has great potential due to its selectivity and flexibility. Unfortunately, existing LD techniques[5,6] make use of an inert atmosphere and/or vacuum processing; thus, they are not directly suitable for low-cost fabrication of solar cells. To overcome these disadvantages, our group developed a LD process working in ambient atmosphere without the need of clean room conditions.[7]

This letter reports a full area laser doped emitter (LDE) solar cell with energy conversion efficiency $\eta=18.9\%$, achieved by combining LD with conventional silicon solar cell processing. At present, the efficiency η is limited by the short circuit current density J_{sc} due to the nontextured cell surface and not by the LDE, as proven by the high open circuit voltage $V_{oc}=677$ mV.

Figure 1 presents the layout of the record LDE solar cell. We use 0.2 Ω cm *p*-type float zone (FZ) silicon wafers with thickness $d=290$ μm for the base. First, a sputtering process deposits a 60 nm pure phosphorus precursor layer on top of the wafer. Then, laser irradiation of a pulsed neodymium doped yttrium aluminum garnet laser with a wavelength $\lambda=532$ nm and a pulse duration $T_p=65$ ns melts the silicon surface up to a depth of about 1 μm. During about 100 ns, the silicon is liquid; phosphorus atoms from the precursor layer diffuse into the melt, creating the *n*-type emitter and thus the *pn* junction at the surface of the *p*-type silicon wafer. Variation of the LD parameters adjusts the shape of the emitter profile and the emitter sheet resistance from 20 up to 400 $\Omega/\square$. After the patented laser scanning process,[8] hydrochloric acid and RCA cleaning[9] remove the residuals of the phosphorus precursor layer. The front and rear sides of the wafer use SiO_2 passivation for low surface recombination. The front contacts consist of a photolithographically opened grid through the oxide and a subsequent evaporation of Ti/Pd/Ag. A stack of 35 nm ZnS and 100 nm MgF_2 at the front side provides an enhanced antireflection coating (ARC).[10] The Al rear contact is made directly to the substrate via a network of contact holes through the rear SiO_2.

Table I compares the characteristics of three high performance laser doped silicon solar cells with different ARC and back contacts. Cell A using SiN_x as ARC, has the lowest cell efficiency $\eta=17.0\%$. In case of cell B, the double layer ARC combined with a full area Al rear contact increase the efficiency to $\eta=18.3\%$ at an open circuit voltage $V_{oc}=660$ mV. The record efficient LDE cell C combines the improved double layer ARC with a passivated rear side, reaching an efficiency $\eta=18.9\%$. The high open circuit voltage $V_{oc}=677$ mV of this cell demonstrates the excellent quality of LDE. All cell data are independently confirmed.

Figure 2 compares the wavelength dependent reflection and external quantum efficiency (EQE) of the three cells A, B, and C from Table I. At wavelengths $\lambda<500$ nm, the SiO_2 passivation (combined with the enhanced double layer ARC at the front side) of cells B, C increases the EQE, due to the lower reflection and surface recombination compared to the silicon nitride layer of cell A. At wavelengths $\lambda>1000$ nm, the passivated rear of cells A, C increases the EQE as a result of lower back side recombination and higher optical back surface reflection. Combining the SiO_2 passivation at the front and rear side results in the high efficient LDE solar cell C with $\eta=18.9\%$.

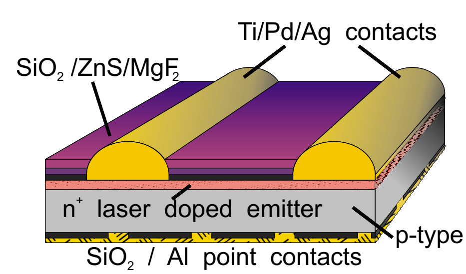

FIG. 1. (Color) Schema of $\eta=18.9\%$ efficient LDE solar cell. The front contacts to the *n*-type emitter consist of a photolitographically opened grid and subsequent evaporation of Ti/Pd/Ag. A double layer of 35 nm ZnS and 100 nm MgF_2 serves as ARC. Silicon dioxide passivates the front and rear providing a low surface recombination. Contact holes through the SiO_2 form the Al rear contact.

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TABLE I. Three high performance LDE silicon solar cells on p-type FZ wafers (resistivity $\rho=0.2\ \Omega$ cm). Open circuit voltage V_{oc}, short circuit current density J_{sc}, FF, and cell efficiency η are independently confirmed by ISE CalLab under standard test conditions (AM 1.5G spectrum, 100 mW/cm^2, 25 °C). The cells vary in ARC and rear contacts; cell area is 4 cm^2. At present, the short circuit current density J_{sc} limits the cell efficiency η due to the nontextured surfaces.

Cell	ARC	Rear contact	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
A	SiN_x	Al point contacts	651	34.0	76.7	17.0
B	ZnS/MgF_2	Al contact	660	34.8	79.6	18.3
C	ZnS/MgF_2	Al point contacts	677	35.2	79.1	18.9

To estimate the potential of LDE, we measure the effective minority carrier lifetimes τ_{eff} of LDE samples, irradiated with different laser pulse energies using the quasi-steady-state photoconductive decay method.[11] The samples consist of FZ p-type silicon wafers with resistivity $\rho=2.8\ \Omega$ cm. Surface passivation is provided by a silicon nitride layer deposited on both sides of the samples. From the measured lifetimes, we extract the emitter saturation current densities J_{0e} of the samples, using the approach proposed by Cuevas.[12]

Figure 3 presents the emitter saturation current densities J_{0e}. The J_{0e} values increase monotonically with decreasing emitter sheet resistance ρ_s. This behavior is related to the increase in doping and thus Auger recombination inside the emitters. Therefore, the lowest saturation current density $J_{0e}=88$ fA/cm^2 occurs at sheet resistance $\rho_s=124\ \Omega/\square$. Assuming that the only source of recombination in LDE solar cells is emitter recombination, allows for the calculation of an upper limit

$$V_{oc,limit}=\frac{kT}{q}\ln\frac{J_{sc}}{J_{0e}} \tag{1}$$

for the open circuit voltage V_{oc}. Here, kT/q denotes the thermal voltage $V_{th}=0.026$ V at room temperature. For the calculation of the $V_{oc,limit}$, we assume a short circuit current density $J_{sc}=35$ mA/cm^2, which is typical for nontextured LDE cells with an excellent ARC. For the lowest saturation current density $J_{0e}=88$ fA/cm^2, the maximum theoretically achievable open circuit voltage reaches $V_{oc,limit}=694$ mV, demonstrating the high quality of LDE. This value is comparable to the world's best silicon solar cells. Thus, we conclude that LD does not lead to one dimensional, two dimensional or three-dimensional lattice defects such as SiP clusters, dislocations, or grain boundaries.

In conclusion, full area LD allows for the fabrication of highly efficient solar cells, using sputtered pure phosphorus precursors. The experimentally achieved open circuit voltage $V_{oc}=677$ mV and a record efficiency $\eta=18.9\%$ verify that our LD process is comparable to furnace diffusion. The $V_{oc,limit}$ data in Fig. 3 demonstrate the experimental $V_{oc}=677$ mV not to be limited by recombination in the laser doped n-type emitter of the cell but by the recombination at the back side contact. At present, the efficiency of our cells is restricted by the short circuit current density $J_{sc}=35$ mA/cm^2, which is a consequence of the non-textured front side. Adding a textured front side would allow us to reach a $J_{sc}\approx 40$ mA/cm^2. Combined with the experimentally obtained V_{oc} and fill factor (FF) values from Table I, this improved short circuit current density would boost the efficiency η above 21%.

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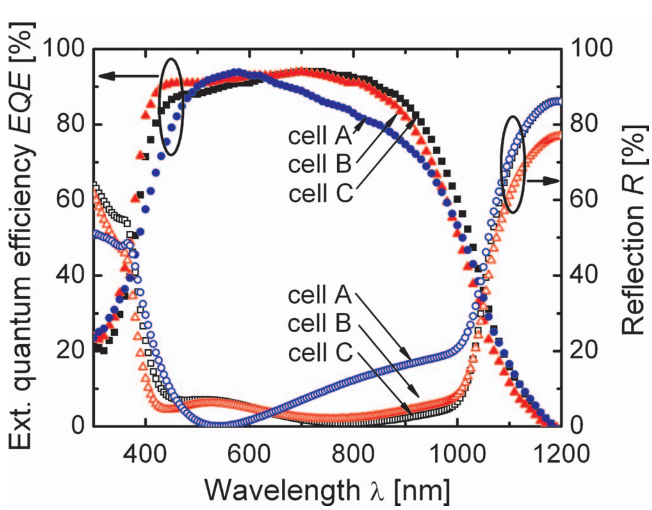

FIG. 2. (Color) Cells A, B, C from Table I. At wavelengths $\lambda<500$ nm, the SiO_2 passivation as well as the double layer ARC of cells B, C enhances the EQE. The passivated rear of cells A, C raises the EQE at wavelengths $\lambda>1000$ nm due to lower back side recombination and higher back surface reflection.

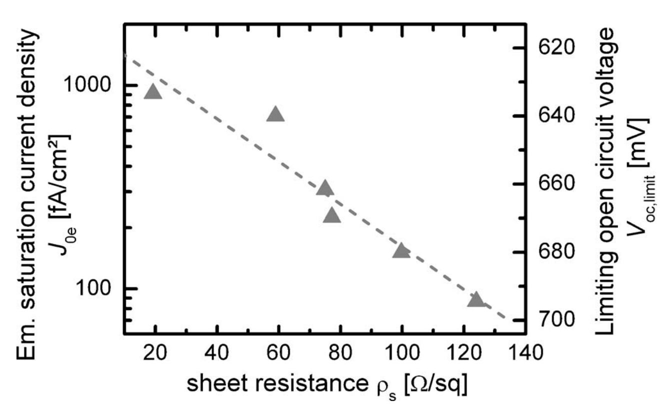

FIG. 3. Emitter saturation current density J_{0e} extracted from lifetime measurements, with $V_{oc,limit}$ calculated from the J_{0e} data using Eq. (1). Increasing sheet resistance ρ_s decreases J_{0e} thus increasing $V_{oc,limit}$. The highest $\rho_s=124\ \Omega/\square$ yields $V_{oc,limit}=694$ mV, showing the high quality of LDE. With such high V_{oc} values and an improved short circuit current density J_{sc} by front side texturing, LDE cells could exceed 21% efficiency.

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