Low Temperature Laser Metallization for Silicon Solar Cells

T. C. Röder, E. Hoffmann, B. Konrad, J. R. Köhler

Institut für Physikalische Elektronik, Universität Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany

Abstract

Laser transferred contacts (LTC) feature low temperature contact formation, in addition to finger widths \( w < 30 \mu m \). The LTC process uses the laser induced forward transfer to deposit the contact metal on the solar cell. Here, a laser heats a thin metal layer through an optically transparent support. Modeling of the temperature distribution in the metal and the transparent glass support during laser heating illustrates that evaporating glass at the metal/glass interface propels the metal to the solar cell surface. The electrical contact to the solar cell emitter is directly formed during the transfer process through the anti-reflection coating of the solar cell. Since the laser transfer is not limited to a special material, a variety of contact metals can be used. Our LTCs are based on “clean” materials without heavy metals, like cadmium or lead. First solar cells with nickel/copper metallization result in a cell efficiency \( \eta = 17.4\% \) and a fill factor \( FF = 77.7\% \).

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1. Introduction

In industrial cell production, screen-printing is the most commonly used method to form the front and back contacts of solar cells. Unfortunately, screen printing limits the width \( w \) to a minimum of \( w \approx 100 \mu m \) of the contact fingers due to their small aspect ratio (height/width) \( A = 1:5 \), thus covering around 7% of the cell surface. For this reason, industrial compatible fine line metallization techniques have to be developed to fill the gap between screen-printing and laboratory techniques. Several different approaches for fine line metallization techniques have been developed [1, 2] or already transferred into production [3]. The ipe developed a new fine line metallization process called laser transferred contacts [4]. This method uses the laser induced forward transfer process (LIFT) [5] to contact the emitter directly through the anti-reflection coating (ARC) without the need of high temperature steps. Afterwards, electroplating thickens the contacts to increase the conductivity, resulting in a contact finger line width below \( w = 30 \mu m \).

This contribution presents deeper insight in the metal transfer process. We give a 2 dimensional simulation of the laser heating of the nickel layer as well as of the glass support in two dimensions. The temperature distribution in the glass and nickel indicates that evaporating glass at the interface between nickel and glass support propels the nickel to the wafer surface. During the transfer process, the contact to the emitter is directly formed through the ARC of the solar cell. Increasing the pulse overlap improves the contact formation as a result of the additional firing by subsequent laser pulses.

2. Experimental

Figure 1 illustrates the principle of LTC. The process consists of two steps: the contact formation using LIFT presented in Fig. 1(a)-(c) and the thickening of the contacts shown in Fig. 1(d). In Figure 1(a), a one-sided nickel coated glass support is placed with the metal side on top of a solar cell. Afterwards, a pulsed green Nd:YVO\(_4\) laser with wavelength \( \lambda = 532 \) nm locally transfers the nickel from the glass support (figure 1(b)) through the ARC, forming the nickel/silicon contact. The width of the laser focus specifies the contact width \( w \), allowing \( w < 10 \mu m \). After contact formation, the glass support is removed (figure 1(c)). Figure 1(d) shows the second step, in which nickel/copper electroplating thickens the contacts to increase the conductivity of the fingers. This step increases the line width \( w \), depending on the desired height of the fingers.

![Fig. 1. Scheme of the laser transferred contacts. (a) A glass support evaporated with a thin Ni layer is placed on top of the solar cell. (b) A pulsed Nd:YVO\(_4\) laser locally melts the metal through the glass support. The resulting gas pressure blasts the metal from the glass support through the ARC. (c) After contact formation, the glass support is removed. (d) Electroplating thickens the contacts, thus increasing the conductivity.](image)
Figure 2 shows a scanning electron microscope picture of the contact design. The laser transfer process contacts the emitter through the ARC with a thin nickel layer of line width $w = 7 \mu m$. After contact formation, electroplating deposits a three $\mu m$ thick nickel layer on top of the contact. The nickel layer acts as diffusion barrier [6] for the subsequently deposited copper. The copper plating increases the contact width $w$ to $w = 21 \mu m$. The contacts exhibit a resistivity $\rho = 1.8 \times 10^{-6} \Omega cm$ as well as a contact resistivity $\rho_c < 1 m\Omega cm^2$.

The first cell characteristics with laser transferred contacts on $4 \ cm^2$ selective emitter solar cells showed the potential of the LTC process [4]. The best cell exhibited a short circuit current density $J_{sc} = 36.5 \ mA/cm^2$ and a fill factor $FF = 77.7\%$. The open circuit voltage $V_{oc} = 612 \ mV$ limits the cell efficiency as a result of the large selectively laser doped [7] areas surrounding the contact fingers. The laser doping melts the silicon surface thus locally increasing the depth and doping concentration of the emitter.

Figure 3 presents contact resistivities $\rho_c$ measured by the transmission line method. For the contact formation, we used a constant pulse energy density $E_p = 1.3 \ J/cm^2$ and different number of irradiation cycles $N_{irr}$. The evaporated nickel thickness on the glass support is $d_{Ni} = 50 \ nm$. The number of irradiation cycles $N_{irr} = 1/(1-Ox/100)$ corresponds to the number of irradiations which process each surface element. Here, $Ox$ is the laser pulse overlap of successive pulses in percent. The decrease in contact resistivity $\rho_c$ with increased $N_{irr}$ results from the “firing” of the nickel particles through the ARC by subsequent laser pulses, thus enhancing the contact formation to the emitter.

Fig. 4 shows optical micrographs of the SiNx anti-reflection coating after etch back of the laser transferred nickel. For the laser transfer, we used a constant laser pulse energy density $E_p = 1.8 \ J/cm^2$ and nickel thickness $d_{Ni} = 230 \ nm$ with different number of irradiation cycles $N_{irr}$. The number of irradiation cycles is varied between $N_{irr} = 5$ and $N_{irr} = 9$. The additional heating by subsequent laser pulses results in an enhanced penetration of the SiNx layer decreasing the contact resistivity $\rho_c$ as shown in Fig 3.
3. Modeling of the transfer process

Figure 5 illustrates the schema of the laser setup using a line shaped laser beam with a typical Gaussian width $w = 8 \, \mu m$ and a length $l = 500 \, \mu m$. A slit adjusts the focus length $f_{\text{fokus}}$ in the range $10 \, \mu m < f_{\text{fokus}} < 500 \, \mu m$. As a result of the line shaped laser beam, the gradient of the laser power density in x-direction is significantly higher than in y-direction. Therefore, the experimental situation justifies to numerically solve the heat transport equation

$$\frac{\partial T(x, z, t)}{\partial t} = \frac{1}{c_p(T) \rho(T)} \left[ \nabla \lambda(T) \nabla T(x, z, t) + \alpha(T) I(x, z, t) \right]$$ \hspace{1cm} (1)

in two dimensions $x$ and $z$. Here with temperature $T$ and time dependent laser power density $I$. The temperature dependent heat capacity $c_p$, mass density $\rho$, thermal conductivity $\lambda$, and absorption coefficient $\alpha$ for nickel and glass are polynomial fits using literature data [8-13]. The absorption of the laser energy in the glass support is neglected, since the absorption coefficient of glass for $\lambda = 532 \, nm$ is very low. The latent heat release during melting and evaporation is simulated by increasing the heat capacity $c_p$ within a temperature interval $\Delta T = 10 \, K$ at the melting temperature $T_{\text{melt}} = 1728 \, K$ and the boiling temperature $T_{\text{boil}} = 3186 \, K$ of nickel. The integral results in the latent heat of fusion $L_{\text{fus}} = 2.9 \times 10^5 \, J/kg$ and latent heat of vaporization $L_{\text{vap}} = 6.3 \times 10^6 \, J/kg$ for nickel [10]. The glass ingredients start to evaporate before the nickel boils, starting with as OH groups incorporated water and the fining agent SO$_3$. Subsequently, the incorporated alkalines and SiO$_2$ evaporate [14]. For simplicity, the simulation includes the latent heat release during glass evaporation as an increase in heat capacity over a broad temperature range starting from 2200 K up to the boiling point of quartz $T_{\text{boil}} = 2503 \, K$. Since the boiling point of nickel is much higher than the temperature needed to evaporate the glass, the glass pressure blasts the underlying nickel from the glass support. X-ray photoelectron spectroscopy measurements indicate a small part of Sodium (Na) on the seed layer after laser transfer. These measurements underline that evaporated glass components blasts the nickel from the support, since Na is part of the glass composition.

Figure 6 shows the temperature distribution in a 360 nm thick nickel layer and the glass support irradiated with a pulse energy density $E_p = 2.8 \, J/cm^2$. The nickel absorbs the laser energy near the interface thus increasing the temperature. Thermal diffusion from the interface heats the nickel layer as well as the glass support. The melt front within the nickel layer moves from the interface to the surface of the nickel layer. The temperature gradient in the glass support is higher than in the nickel layer, since the thermal diffusion in glass is much lower than in nickel. The glass support reaches room temperature after several hundred nanometers. The simulation confirms the measured threshold energy of $E_{\text{th}} = 1.4 \, J/cm^2$

![Fig. 4: Optical micrographs of the SiN$_x$ anti-reflection coating after etch back of the laser transferred nickel. Increasing the number of irradiation cycles $N_{\text{irr}}$ increases the contact area, thus enhancing the contact resistivity as shown in Fig. 3.](image-url)
for nickel ablation. For $E_p < E_{th}$, the temperature distribution has a maximum temperature at the interface below 2300 K, which is not high enough to build up the needed pressure for the nickel transfer.

Fig. 5: Schema of the laser setup. We use a line shaped laser beam with wavelength $\lambda = 532$ nm and a typical Gaussian width $w = 8 \mu m$ and length $l = 500 \mu m$. A slit adjust the focus length $l_{focus}$ on the sample.

Fig. 6: Simulated temperature distribution in the glass support and a 360 nm thick nickel layer. The maximum temperature is reached near the glass/nickel interface due to the high absorption coefficient of nickel.

4. Conclusion

The evaporated nickel layer absorbs the laser irradiation near the nickel/glass interface as a result of the high optical absorption coefficient $\alpha$ increasing the nickel temperature at the interface. The heat diffuses from the interface into the nickel layer as well as into the glass support. Since the evaporation of the glass components starts below the boiling point of nickel, evaporating glass propels the nickel to the solar cell. The transferred nickel particles contact the emitter through the antireflection coating. Additional heating by subsequent laser pulses enhances the contact formation by firing the deposited nickel layer through the SiNx layer. Since only a small part of the surface is heated during contact formation, the LTC process is a low temperature metallization technique – the whole solar cell stays at room temperature during processing. First solar cells with nickel/copper metallization result in cell efficiencies $\eta$ up to $\eta = 17.4\%$ and fill factor $FF = 77.7\%$. Hence, the LTC process is promising for industrial production, particularly if transparent foils replace the glass support, enabling roll-to-roll processing.

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References


