Energy Technology

SUPPLEMENTARY INFORMATION

Nickel silicide Rear Metallization Impact on the Crystalline Silicon Solar Cells Series Resistanc

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Elemental quantification of Nickel-mono silicide (NiSi):

Elemental quantification is carried out on the samples which achieved the minimum sheet resistance value ~ 2.8 Ω/sq by depositing 50 nm of Ni then annealed at 450 ^{o}C. The samples were prepared using FEI Helios NanoLab 400S FIB/SEM dual-beam system using Pt/C deposition. Then High-angle annular dark-field imaging (HAADDF) in a scanning transmission electron microscope (STEM) images (see Figure S1(a)) were obtained using an FEI Titan ST electron microscope operated at 300 kV, indicating an average thickness of NiSi of ~ 44 μm. Additionally, Energy-dispersive X-ray (EDX) spectroscopy point analysis at P1 shows the elemental composition of silicon and nickel which have an approximately 49.24% and 50.76% atomic percentages, respectively, indicating that around 22 nm of silicon is consumed for NiSi structure as shown in Figure 1(b) and Table S1.

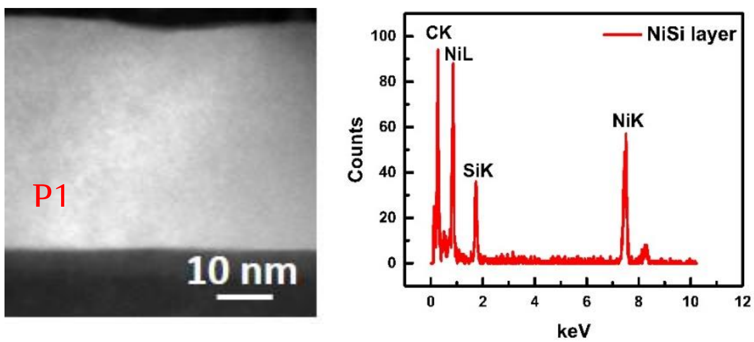

Figure S1 (a) HADDF-STEM image of NiSi layer **(b)** Energy-dispersive X-ray (EDX) of NiSi in terms of weight percentages.

Table S1. Weight percentages of Ni and Si at the point (P1)

point	Element	Weight	Atom%
P1	Si	0.32	49.24
	Ni	0.68	50.76

SIMS depth profiling of NiSi/Cu rear contact:

The fabrication of the (NiSi/Cu) contact on the rear textured silicon surface was verified by performing SIMS. The depth profiling experiment was carried out using a Dynamic-SIMS instrument (Hiden Analytical Ltd., Warrington, UK) under UHV conditions (10^{-9} Torr). The depth profiles of Cu, NiSi, Ni ,B and silicon as shown in Figure S2. However, the depth profiling has low accuracy in terms of the depth and sharp interfaces due to the high roughness of the rear side because of the random pyramidal Si surface.

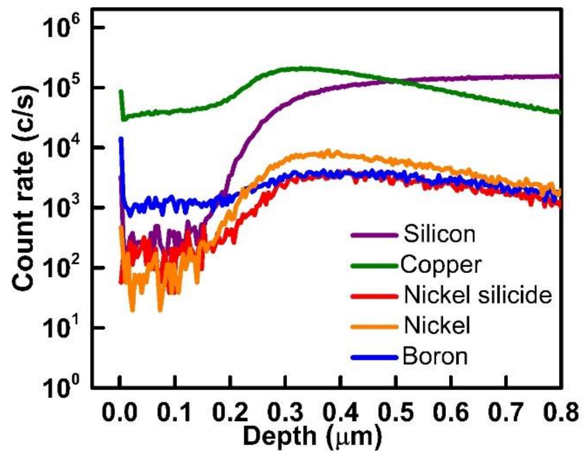

Figure S2: SIMS depth profiling of NiSi/Cu on the rear side of the silicon

Series resistance determination (R_s) methods:[1]

1- **Comparison of dark and one sun JV-curves**:

The principle of this method is based on a voltage difference at maximum power point (mmp) of one sun and the dark JV-curves as explained in the main manuscript. Fiure. S4 and Table S2 show the variation of the electrical performance parameters at the maximum power |mpp|. Applying this method shows that $R_{S:light\_dark}$ is reduced for NiSi/Cu rear contact by 0.68 Ω.cm^2 compared to screen printed Ag.

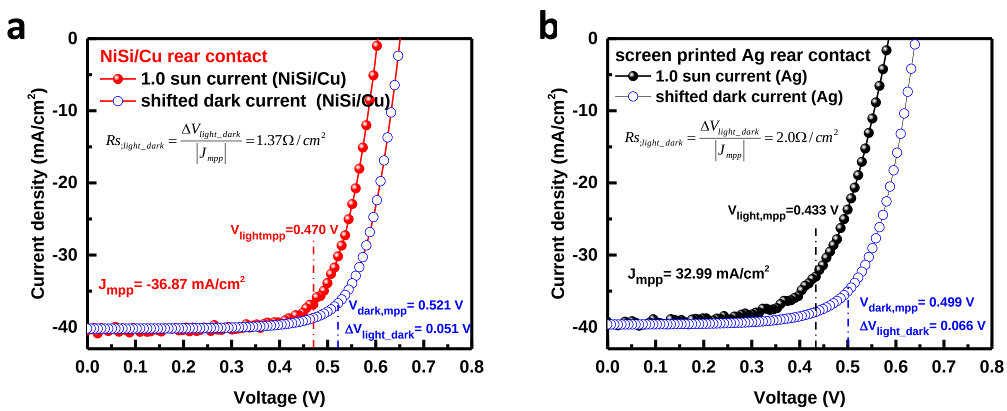

Figure S3: JV-curves of one sun and J_{SC} shifted dark measurements. (a) NiSi/Cu rear contact (b) screen printed Ag.

Table S2: Variation of electrical performance parameters at the maximum power |mpp| value taken for series resistance determination (RS;light_dark) for dark and 1 sun intensity illumination.

Rear contact	shifted dark measurements		1.0 sun illumination				
	|mpp| (mΩ.cm^2)	**$V_{dark,mpp}$ (V)**	**|mpp| (mΩ.cm^2)**	**$V_{light,mpp}$ (V)**	**J_{mpp} (A/cm^2)**	**ΔV_{light_dark} (V)**	**$R_{S;light\_dark}$ (Ω.cm^2)**
NiSi/Cu	19.148	0.521	17.33	0.470	0.0368	0.051	1.38
Screen printed Ag	17.52	0.499	14.73	0.433	0.0329	0.066	2.06

2- Comparison of two JV-curves measured at one and 0.7 sun illumination intensities:

This method is based on the comparison of two JV-curves measured at different illumination intensities as shown in Figure S5(a and b) for NiSi/Cu rear contact and screen printed Ag, respectively. Measuring the JV-curves at different illumination intensities (1 and 0.7 sun) ends in two shifts between them. The first shift is in the current density due to the difference in the photo-generated current which is proportional to the incident illumination intensity. The second shift is in voltage which is caused by the smaller series resistance loss, at a lower light intensity: $\Delta V = R_{s,light}\Delta J_{sc}$. Where $\Delta J_{sc}$is the variance in the two short-circuit current densities. Each JV point [J_x,V_x] lies at a fixed distance ΔJ (10, 15 and 20 mA) from the short-circuit current (e.g. $J_x = J_{SC}–\Delta J$) where ΔJ is marked on each curve. Table S3 presents the [J_x,V_x] points and the corresponding $R_{S;int:var}$ calculated from:

$$R_{s,int:var} = \left|\frac{\Delta V}{\Delta J_{sc}}\right|$$

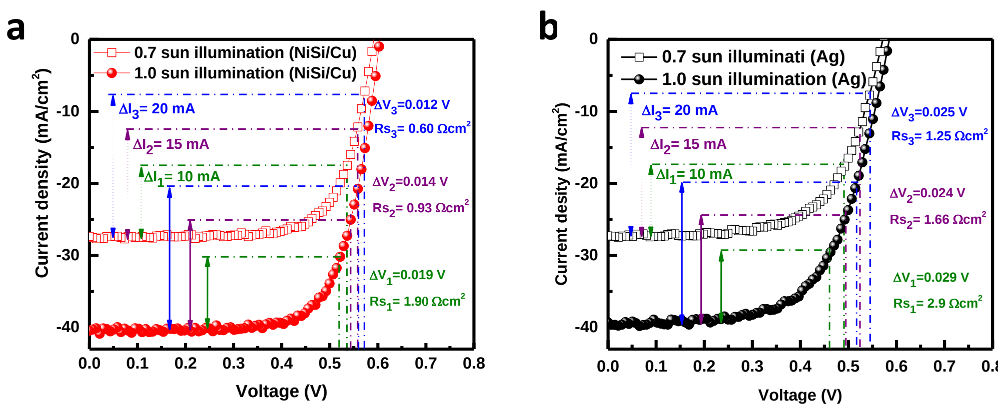

Figure S4: JV-curves of one sun and J_{sc} shifted dark measurements. (a) NiSi/Cu rear contact (b) screen printed Ag.

Table S4. Variation of electrical performance parameters measured with respect to short circuit current J_{SC} density taken for determination *of* the average series resistance ($R_{s;int:var}$) value for two different light intensities (1 and 0.7 sun)

Rear contact	0.7 sun illumination			1.0 sun illumination					
	J_{sc} (mA/cm²)	J_1 (mA/cm²)	V_1 (V)	J_{sc} (mA/cm²)	J_2 (mA/cm²)	V_2 (V)	ΔJ (mA/cm²)	ΔV (V)	$R_{s;int:var}$ (Ω.cm²)
NiSi/Cu	27.520	17.520	0.536	40.18	30.18	0.517	10	0.019	1.90
		12.520	0.557		25.18	0.543	15	0.014	0.93
		7.520	0.572		20.18	0.560	20	0.012	0.6
						$\overline{R_s}$ (NiSi/Cu)			**1.14**
Screen printed Ag	27.41	17.41	0.493	39.34	29.34	0.464	10	0.029	2.90
		12.41	0.524		24.34	0.495	15	0.024	1.66
		7.41	0.545		19.34	0.515	20	0.025	1.25
						$\overline{R_s}$ (screen printed Ag)			**1.93**

Table S5. The simulation parameters used in investigating the contact resistance impact on the JV-behavior.

Properties	Doping (cm^{-3})
n-layer (emitter)	N_d=5×10^{22} (1um thick)
c-Si (p-type)	2×10^{15}
p-layer (collector)	N_A=5×10^{22}

References:

[1] aD. Pysch, A. Mette, S. W. Glunz, *Solar Energy Materials and Solar Cells* **2007**, *91*, 1698-1706; bR. J. Handy, *Solid-State Electronics* **1967**, *10*, 765-775.