Performance of Solar Cell Grids based on Ag, Au, and Al for Cost-Effective Manufacturing

Marianna Raappana
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
marianna.raappana@tuni.fi

Arto Aho
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
arto.aho@tuni.fi

Timo Aho
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
timo.aho@tuni.fi

Riku Isoaho
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
riku.isoaho@tuni.fi

Elina Anttola
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
elina.anttola@tuni.fi

Ninja Kajas
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
ninja.kajas@tuni.fi

Ville Polojärvi
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
ville.polojarvi@tuni.fi

Antti Tukiainen
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
antti.tukiainen@tuni.fi

Mircea Guina
Optoelectronics Research Centre
Physics Unit, Tampere University
Tampere, Finland
mircea.guina@tuni.fi

***Abstract*—We report on the performance of front contact grids based on Ag, Al, and Au applied to III–V multijunction solar cells. We compare their suitability as grid metals from different perspectives, including price, mass-to-conductivity ratio, and abundance. The grid functionality was evaluated by performing charge transport experiments under simulated sunlight. The best solar cell performance was obtained for Ag contacts. On the other hand, Al and Ag provide the most cost-effective approach: when compared to Au, the cost for the grid material for equal conductivities is only about 1.1% for the Ag contacts, and 0.7% for Al.**

Keywords—solar cell, III–V heterostructures, grid design, cost-effectivity

I. INTRODUCTION

Photovoltaic space generators require solar cells performing with high reliability and providing highest possible efficiency. To this end, high-efficiency III–V multijunction solar cells are the choice for space applications [1], owing to their beneficial properties such as radiation hardness and high power-to-mass ratio. While the optimization of the heterostructures and cell architectures remains a constant effort in terms of new developments, the front contact grid is less a matter of optimization on the research front, apart from geometrical aspects. Considering grid optimization, power losses originating from different sources need to be taken into account [2]. These include:

1. *Emitter/window layer resistance,*
2. *Grid metal resistance,*
3. *Contact resistance between the metal and semiconductor,*
4. *Metal grid shadowing.*

In this respect, also the choice of the grid materials should be carefully considered in order to improve the solar cell performance, while also taking into account for example the cost metrics.

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When comparing different metals for their suitability to be used as grid metals, significance may arise for example from electrical conductivity, solderability, long-term durability, ecology, abundance, and cost-effectiveness. Conventionally, grids are fabricated using Ag or Au. Au has the advantage of being inert but has a high price and low abundance, whereas Ag has higher electrical conductivity, higher abundance, and lower market price (see Table I). In addition to Au and Ag, there are also other optional grid metals, of which Al is an attractive choice [3] for its lower price, higher abundance, and lower density, thus enabling a more cost-effective and light-weight design. On the other hand, with respect to grid dimensions, smaller cross-sectional area of the grid fingers is needed with more conductive metals, leading to savings in material consumption and to a smaller shadowing effect. Also, high electrical conductivity-to-mass ratio could be highly beneficial especially concerning thin film solar cells, where grid metals make a larger part of the device mass. Although Ag is the clear winner in terms of electrical conductivity, Al could be highly beneficial in terms of costs and high power-to-mass ratio of the final device.

TABLE I. VALUES OF ELECTRICAL CONDUCTIVITY, DENSITY, MARKET PRICE (PURITY 99.99%) AND ABUNDANCE IN EARTH'S CRUST FOR Au, Al, AND Ag.

Metal	Properties			
	Electrical conductivity[a] (S/m) [4]	*Density (kg/m³) [5]*	*Market price[b] (€/g) [5]*	*Abundance (m-%) [6]*
Au	4.52×10^{7}	19.32×10^{3}	56.7	4×10^{-7}
Al	3.77×10^{7}	2.7×10^{3}	1.5	8.23
Ag	6.30×10^{7}	10.5×10^{3}	3.0	7.5×10^{-6}

a. Values at 20 °C.

b. Example of market prices with purity 99.99%.

In this work, Au, Ag, and Al front contact grids are fabricated on triple-junction III–V solar cells to study their functionality as grid metals. The solar cell performance is assessed in terms of current-voltage (*I-V*), both at one sun and under concentration.

II. Experimental

The front contact grids under investigation were fabricated on GaInP/GaAs/GaInNAsSb solar cells that were grown on p-GaAs substrate with Veeco GEN20 molecular beam epitaxy system. More detailed description of the growth can be found in [7, 8]. Three different metals for the front contact grid were studied: Au, Al, and Ag. The grid configurations are presented in Table II. The contact grids were fabricated on highly doped n-GaAs due to which no alloying was required to form an ohmic contact between the semiconductor and metals. Ni was used as an adhesion layer, whereas Au was used in the Ag sample both for adhesion and as a capping layer. All the metals were deposited by electron beam evaporation except for Ag which was deposited by resistive evaporation. Grid patterns were fabricated using a standard photolithography process.

TABLE II. Solar Cells with Different Front Contact Grid Configurations.

Sample	Grid configurations	
	Grid design	***Metal layer thicknesses (nm)***
Au	Ni/Au	10/1500
Al	Ni/Al	10/1500
Ag	Ni/Au/Ag/Au	10/100/1500/50

Subsequent to the metal contact deposition, solar cell components were prepared with mesa isolation by etching and provided with a TiO_x/SiO_x antireflection coating by electron beam evaporation. The solar cell components were characterized with *I-V* measurements using a 7 kW OAI Trisol solar simulator under AM0 spectrum both at one sun (ASTM E490) and under several concentrations.

III. Results and Discussion

The *I-V* curves measured at one sun and at 680 suns are shown in Fig. 1 for solar cells with Al, Ag, and Au contacts. The one-sun characteristics of the solar cells with different metals are very similar. Under concentration, Ag provides the highest performance whereas Au shows minor degradation, and Al has already clearly deteriorated, most likely due to series resistance effects.

The overall performance of the solar cells is well described by fill factors which are plotted as a function of concentration in Fig. 2. As it can be seen, Ag is superior to Au, while Al shows greater decline in the solar cell performance at higher concentrations.

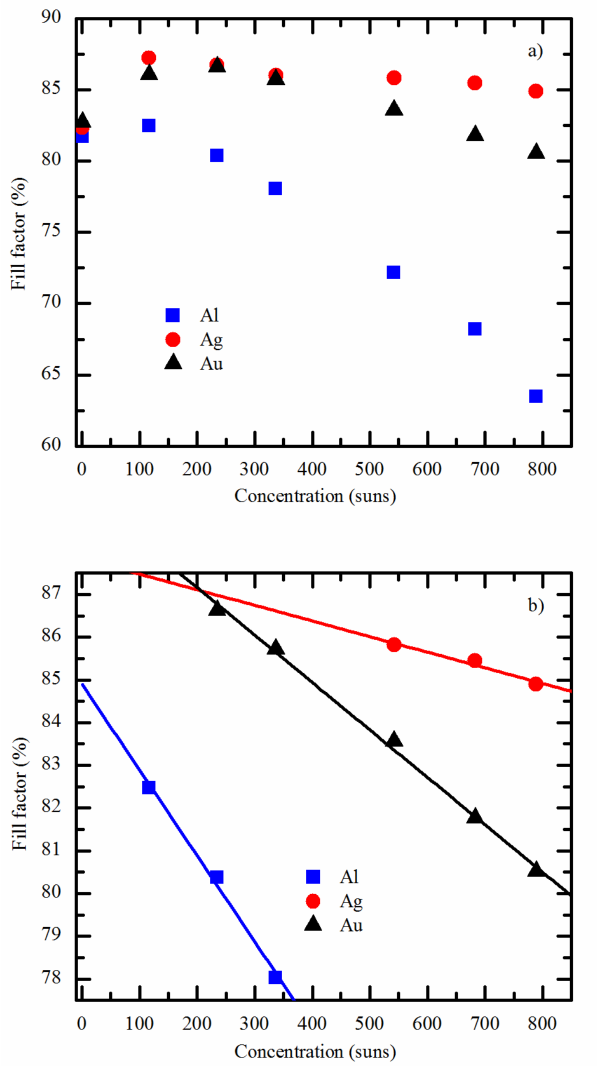

Fig. 2. a) Fill factors presented as a function of concentration. b) Fitted lines on the fill factor data points.

To further compare the grids, fitting was applied on fill factor values (Fig. 2) to derive comparable ratios for series resistance (R_s) values relative to Au, yielding the following ratios: R_s(Ag)/R_s(Au)=0.38 and R_s(Al)/R_s(Au)=1.75. This indicates that in terms of volume, less Ag would be required to obtain the same conductivity as Au or Al, which would be highly beneficial when aiming at minimal surface coverage and cost-effectiveness. When taking into account metal

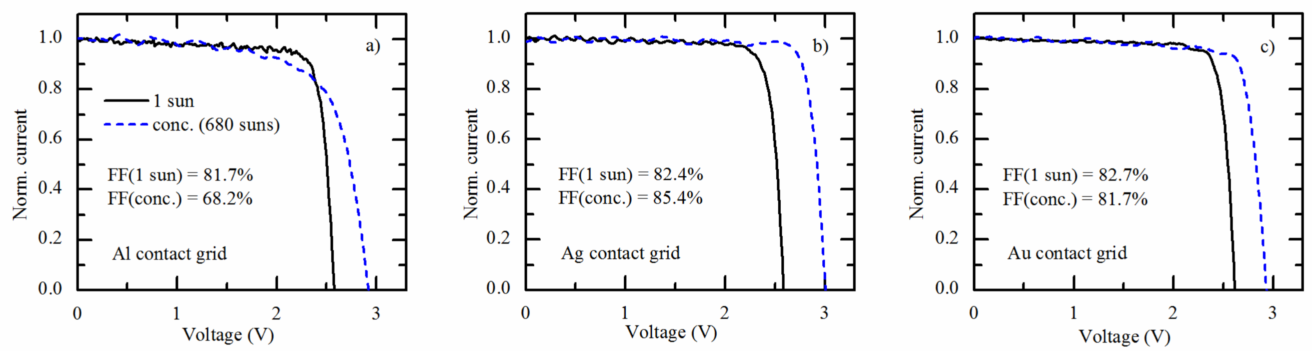

Fig. 1. Normalized *I-V* curves for solar cells with a) Al, b) Ag, and c) Au grid at one sun and at 680 suns.

densities, similar conductivities would be obtained with 21% and 24% of the Au grid mass when using Ag and Al grids, respectively. Considering the current market price of the studied metals and the material consumption relative to achieve comparable conductivities, the grid material expense would be only about 1.1% and 0.7% of the price of Au for Ag and Al, respectively. It should be noted that the market values used represent examples with certain metal purity. Thus, the figures concerning cost-effectiveness should be considered as indicative.

IV. CONCLUSIONS

In terms of cost-effectiveness, Ag and Al grids are proven to be superior to Au grid. When considering solar cell performance, the Ag grid showed the best performance with highest fill factor values and therefore is the most optimal choice for high-efficiency solar cells. Although the Al grid would be the most cost-effective option with clearly highest abundance, the inferior photovoltaic performance could prevent practical deployment in applications.

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