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Front metal finger inhomogeneity: its influence on optimization and on the cell efficiency distribution in production lines

Y. Chen[a], Y. Yang[a], W. Deng[a], A. Ali[b], P.J. Verlinden[a], P.P. Altermatt[a]*

[a] *State Key Laboratory for PV Science and Technology, Trina Solar, Changzhou, Jiangsu Province, 213031, P.R. China*
[b]*Department of Physics, Government College University Faisalabad, 38000 Faisalabad, Pakistan*

Abstract

A model is developed for simulating the inhomogeneity of front metal fingers and its influence on the performance of mass-produced crystalline silicon solar cells. First, it is shown by numerical device simulations that, in modern cell design, the optimal number of fingers will be increasingly determined by the emitter sheet resistivity and to a lesser extent by other geometries of the metallization (such as finger width, their cross-sectional area *A*, and the number of bus bars). An example from production shows that the relationship between finger width and the amount of screen-printing paste can be inferred from the data cloud containing short-circuit current and fill factor values of fabricated cells. A logistic function is introduced to fit a broad range of cross-sectional finger shapes. With all this as input, spice simulations are preformed to elucidate the dynamics of cell efficiency in dependency of cross-sectional finger area *A*. The model for finger inhomogeneity is illustrated with a failure analysis. Then, it is shown that finger inhomogeneity contributes only to a small extent to the observed variations in mass production, so the metal fingers can be designed with considerably smaller *A* to save silver without causing a too large spread in efficiency. Finally, a desirable near-future target of $A \approx 300\ \mu m^2$ is derived from a combination of modeling and a literature collection of metallization data. It will not be necessary in future cell design to increase the number of fingers beyond about 155 (equivalent to a finger pitch of about 1 mm), regardless of the number of bus bars or of a multi-bus bar design. Comparing the simulations with the trend in literature data suggests that screen-printing will be the moving target in metallization for some time to come. Mainly economic pain due to high silver prices may favor a transition to (near) silver-free printing techniques.

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Keywords: Silicon solar cells; device simulation; metallization;screen-printing; silver

* Corresponding author. Tel.: +86-519-8158-7679.
E-mail address: pietro.altermatt@trinasolar.com

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1. Introduction

The optimization of the front metal grid influences mainly the short-circuit current density J_{sc} and the fill factor *FF* of the current-voltage (IV) curve of solar cells due to the well-known offset between shading and resistive losses. The open-circuit voltage V_{oc} may be influenced only in cases where the amount of recombination at the front metal contacts varies with grid optimization and if it contributes significantly to the total recombination losses of the cell. It is well known that these IV parameters may also be affected by other parts of the cell than by the front metallization. For example J_{sc} may vary in cell production due to variations in the passivation of the front surface [1], while *FF* may vary due to Si/metal contact resistivity or a variable amount of oxygen and of boron-oxygen (B-O) recombination centers, which cause an injection-dependent and hence a voltage-dependent lifetime. In this paper, we only take variations due to the front metallization into account.

A detailed paper treating inhomogeneity within the front metal grid is the recent one by Wong et al. [2], using the GRIDDLER model. Another paper in the awareness of the authors is Ref. [3]. In our work, the inhomogeneity of the front metal fingers is treated with a SPICE model, which has an IV curve from a numerical device model as input. The paper emphasizes on the caused distribution of J_{sc} and *FF* in mass production and on consequences on metallization and cell design in near future.

Nomenclature

A	Cross-sectional area of a metal finger [μm^2].
a	Curvature factor used in the fitting of cross-sectional finger shapes with Eq. (1).
F	Filling factor of the finger, i.e. A divided by the rectangle spanned by the finger width and finger height.
f	Fractional parameter for quantifying variations of A relative to a fixed A_0, $A = fA_0$.
N	Number of metal fingers on a 156×156 mm^2 large cell.
$R_{s.int}$	Internal lumped series resistance of the cell [Ωcm^2], including Si/metal contact resistance.
$R_{s.seg}$	Resistance [Ω] of a finger segment represented by a resistor in the SPICE simulation.
w_{min}	Minimal width [μm] of metal fingers when printed with hardly any paste, as indicated in Fig. 2

2. Optimal number of fingers

The bases of this paper are two and three dimensional numerical simulations of the semiconductor part of monocrystalline silicon solar cells. The simulations are performed with the software SENTAURUS DEVICE using the silicon parameters of Ref. [4] including an update in the model for the Al-alloyed back surface field (BSF) [5] and for Auger recombination [6]. We choose an advanced cell design for standard production. Without metallization, the cell has a J_{sc} = 40 mA/cm^2 due to a typical nitride antireflection coating, and the cell efficiency is adjusted to 21% by choosing a good selective emitter, leading to both a V_{oc} = 640 mV and a rather high internal lumped series resistance $R_{s.int}$. See Fig. 1 for the simulation results in dependence of the number of front metal fingers. $R_{s.int}$ varies mainly due to the emitter sheet resistivity, and J_{sc} due to a varying amount of recombination in the emitter because the width of its highly-doped n^{++} part is kept constant at 200 μm to accommodate alignment tolerances. Further details of the semiconductor part of the cell are irrelevant to our metallization study and are not given here.

With adding the metallization, J_{sc} becomes approximately 38 mA/cm^2 and cell efficiency is 20%, as is expected from standard cells in 2018 according to the ITRPV roadmap [7]. The fill factor reaches about 80.5% because it is assumed that the B-O complex in the p-type wafer is thoroughly deactivated.

A crucial step in grid optimization is adjusting the number of metal fingers N (or equivalently the finger pitch). It is important to note that in advanced cell designs with a good emitter, the optimum N is mainly imposed by the high emitter sheet resistivity and only to a minor extent by the finger width or other metallization geometries. This has not been the case in cell designs with a low emitter sheet resistivity.