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Metal nano-grids for transparent conduction in solar cells

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ABSTRACT

A general procedure for predicting metal grid performance in solar cells was developed. Unlike transparent conducting oxides (TCOs) or other homogeneous films, metal grids induce more resistance in the neighbor layer. The resulting balance of transmittance, neighbor and grid resistance was explored in light of cheap lithography advances that have enabled metal nano-grid (MNG) fabrication. The patterned MNGs have junction resistances and degradation rates that are more favorable than solution-synthesized metal nanowires. Neighbor series resistance was simulated by the finite element method, although a simpler analytical model was sufficient in most cases. Finite-difference frequency-domain transmittance simulations were performed for MNGs with minimum wire width (w) of 50 nm, but deviations from aperture transmittance were small in magnitude. Depending on the process, MNGs can exhibit increased series resistance as w is decreased. However, numerous experimental reports have already achieved transmittance-MNG sheet resistance trade-offs comparable to TCOs. The transmittance, neighbor and MNG series resistances were used to parameterize a grid fill factor for a solar cell. This new figure of merit was used to demonstrate that although MNGs have only been employed in low efficiency solar cells, substantial gains in performance are predicted for decreased w in all high efficiency absorber technologies.

1. Introduction

Transparent conduction is crucial to many optoelectronic devices, and is particularly vital to the photovoltaics (PV) community: efficient solar cells require high optical transmittance of the solar resource along with high electrical power transmission. Transparent conducting oxides (TCOs) are the industry standard for Si heterojunction with intrinsic thin layer (HIT), CdTe, $Cu(In,Ga)(Se,S)_2$ (CIGS), and hybrid organic-inorganic perovskite technologies. The most common TCO is indium tin oxide (ITO; \$1.6 billion sales in 2013 [1]), but it has vulnerabilities: vacuum sputtering makes it relatively capital-intensive, with low material utilization of expensive In [1], brittleness makes it unusable in flexible devices [2], and chemistry makes it incompatible with some materials (such as crystalline Si [3] and organic semiconductors [4]). The most popular alternatives to ITO also have fundamental drawbacks: Al:ZnO is unstable in damp heat and soda-lime glass environments [5–8], $F:SnO_2$ has inferior transmittance (T)-sheet resistance (R_{sh}) trade-offs [5], Ag nanowires are highly unstable under typical operating conditions [9–16], and carbon nanotubes and graphene are both too resistive for solar cells [17]. Besides TCOs, metal grids have been deployed to conduct high currents over long distances in PV modules for decades. For grids, smaller dimensions yield better performance [18], so the industry-standard screen printing resolution (down to 30,000 nm [19]) has historically limited performance. This limitation has recently been lifted, as new lithography strategies have emerged to fabricate metal nano-grids (MNGs). MNGs can have better T and R_{sh} than metal macro-grids and ITO in theory and practice [20–28], use cheap processes [27,29,30], use flexible substrates [31–33], and exhibit low degradation rates under mechanical stress and damp heat [27,34]. The MNGs are *not* contiguous films, so grid thickness can be designed to reduce MNG resistance with less effect on optical transmittance, relative to conducting films. The patterning processes lead to robust, well-formed wires and junctions, relative to solution-synthesized Ag nanowires. MNGs can also replace opaque metal films to enable new solar cell architectures, multiple junctions, and bifacial devices. While quality p-type TCOs have eluded the scientific community for decades due to large hole effective masses [35], the MNG work function can easily be tailored for n- or p-type contacts.

A variety of processes and metals have already been used to fabricate MNGs with better T-R_{sh} trade-offs than ITO (detailed below), but they have only been used as stand-alone transparent contacts in solar cells with efficiencies up to 7.0% [36,37], less than half that of most commercial modules. Moreover, the direct comparison of ITO and MNG transmittance-R_{sh} curves is misleading, as grids are not homo-

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genous films. This inhomogeneity induces more resistance in the adjacent semiconducting layer ("neighbor"), but it also lifts the constraint of thickness being tied to transmittance. The present work proposes a general method for calculating a metal grid figure of merit that includes neighbor *and* grid resistance, with particular focus on MNGs and high efficiency solar cells. Analytical calculations are compared with simulation results for neighbor resistance, MNG transmittance, and MNG resistance. These are used to establish fundamental limits for MNG performance, and identify the best MNG designs. The figure of merit is then used to analyze potential MNG gains for every high efficiency PV absorber technology: silicon, HIT silicon, CdTe, CIGS, GaAs, and hybrid organic-inorganic perovskites.

2. Methods

Neighbor resistance calculations and simulations are described below. Previous analyses of neighbor series resistance considered how a two- or three-dimensional diode is affected by a grid in detail [38–49]. In contrast, the limits of grid performance were presently examined in terms of MNG process-relevant parameters. MNG sheet resistance was simulated by using the finite element method (FEM) to solve for electric potential throughout the MNG volume, and integrating it over a given current. A uniform current source flowed in the plane of the solar cell and traversed some distance L, assumed to be much greater than the MNG thickness. The optimal conduction direction was used for each grid shape. To combine neighbor and MNG resistances, it was assumed that the neighbor/MNG stack does *not* behave like two films in parallel [50], but is instead limited by neighbor lateral resistance in aperture areas, and then by lateral MNG resistance in the obscured areas (i.e. resistors in series) [51]. A resistivity of 700 Ω cm was used for the CdS neighbor—near the middle of the wide range reported at 1 sun for chemical bath deposited CdS [52–55], although it was an order of magnitude greater than resistivity values used in previous simulations [56–63]. The CdS thickness was set to 100 nm to avoid potential pinholes and shunts. The MNG metal was copper with $1.68 \cdot 10^{-6}$ Ω cm [28] and 50 nm thickness, unless noted. A short-circuit current density of 40 mA/cm^2 [64] and open-circuit voltage of 750 mV [65] were used. The finite-difference frequency domain (FDFD) method was used to simulate two-dimensional electromagnetic fields. Plane waves incident on the air/MNG/air or air/MNG/substrate structures were simulated for TE and TM polarization of 280–1360 nm wavelengths, chosen to bound the appreciable power in the air mass 1.5 spectrum. Surfaces with no roughness were assumed for all simulations. Periodic boundary conditions were used on the sides of a single MNG unit cell. In all cases, simulation domains and mesh sizes were optimized to reduce error.

3. Results

3.1. General approach

The optimal design for a grid or TCO minimizes the total power loss due to (1) resistance in the neighbor layer (R_{neighb}), (2) diminished transmittance through the transparent conductor, and (3) resistance in the transparent conductor. TCO films typically cover the neighbor layer homogenously, making R_{neighb} negligible. On the other hand, grids have inhomogeneity that greatly increases lateral conduction in the neighbor. The only way to mitigate this R_{neighb} is to reduce the distance between grid wires—this is the reason MNGs are advantageous. The limit to this trend is where the assumptions used in deriving it break down, taken in this work to be a minimum wire width, w of less than 50 nm. Wires of smaller width are more difficult to process, exhibit increased resistivity (relative to bulk ρ_{metal}) due to increased grain boundary, surface, and impurity scattering [66,67], increased junction resistance (similar to Ag nanowires) [1], depressed melting temperatures [12,16], and high surface area-to-volume ratios that lead to increased degradation rates [10,13,15]. The exact limitations must ultimately be identified experimentally for specific processes, and the present work should guide the choice of those experiments while motivating them with performance gain estimates. Below, the prospect of replacing TCOs with MNGs in CIGS and CdTe solar cells is examined in detail, but all results can easily be scaled for other applications.

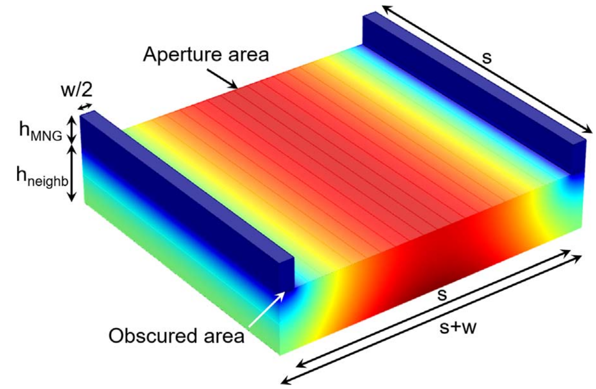

Fig. 1. Schematic of a grating MNG showing aperture area, obscured area, w, s, h_{MNG}, and h_{neighb}, as used in the text.

Widely diverse grid shapes have been used in previous experiments and simulations: gratings [68], squares [20], rectangles [69], triangles [70], hexagons [71], truncated hexagons [72], hexagonal-packed circles [73], square-packed circles [74], multi-sized circles [21], tetrakis squares [70], disordered circles [75], random wires [37], fractals [76], hierarchical shapes [77], busbar with fingers [78], and various other shapes [79,80]. The grating, triangle, hexagon, square, and hexagonal-packed circle were investigated in the present study. Rectangles with 2x and 4x the square length were also examined, where the widths were reduced by 2x and 4x, respectively. Three parameters completely defined each shape, only two of which were independent: w, T_{aper}, and space between wires (s; where the unit cell period is the sum of w and s). An example is shown for the grating in Fig. 1.

3.2. Neighbor resistance (R_{neighb})

Wyeth first outlined the general procedure for calculating neighbor resistance for any grid shape [51]. His analysis made several approximations: current generation is uniform throughout the neighbor volume, but only in aperture areas, resistance is dominated by lateral current flow (in the plane of the solar cell), planes dividing aperture and obscured areas are effectively grounded, and neighbor diffusion current is negligible. These assumptions lead to an equation for potential in the neighbor layer:

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = -\frac{\rho_{neighb} \bullet J}{h_{neighb}} = -R_{sh,neighb} \bullet J \tag{1}$$

This equation can be solved by setting potential at the aperture/obscured boundaries to zero ($\varphi(x, y) = 0$), or setting the potential's normal derivative to zero at the uncontacted boundaries (e.g., $\partial\varphi(x, y)/\partial y = 0$). A simple analytical solution results for the grating, which can be multiplied by current density and integrated over the aperture area to find Ohmic power dissipation:c

$$\varphi = \frac{R_{sh,neighb} \bullet J}{2} \bullet (s \bullet x - x^2) \tag{2}$$

$$P_{neighb} = \int_{x=0}^{x=s} \int_{y=0}^{y=s} \frac{R_{sh,neighb} \bullet J^2}{2} \bullet (s \bullet x - x^2) \bullet dx \bullet dy = \frac{R_{sh,neighb} \bullet J^2 \bullet s^4}{12} \tag{3}$$

The voltage loss is power divided by the product of current density and aperture area ($V_{neighb} = P_{neighb}/(J \bullet s^2)$). The neighbor power loss density and series resistance are also referred to the aperture area ($\underline{P}_{neighb} = P_{neighb}/s^2$ and $R_{neighb} = P_{neighb}/(J^2 \bullet s^2)$). For more complicated