Photon Management Structures Based on Interference Lithography

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Abstract

Since micro- and nanostructures for photon management are of increasing importance in novel high-efficiency solar cell concepts, structuring techniques with up-scaling potential play a key role in their realization. Interference lithography and nanoimprint processes are presented as technologies for origination and replication of fine-tailored photonic structures on large areas. The combination of these processes is presented as a feasible route to generate high-efficiency honeycomb textures on multicrystalline silicon.

1. Introduction

Photon management structures are of increasing importance for solar cells, as thinner wafers or even thin absorbing films are used and high external quantum efficiencies over the whole usable spectrum are required for high solar cell efficiencies. The texturing of silicon solar cells is a well-known measure to minimize optical losses and thus increase cell efficiencies. Whereas in the laboratory, template-based texturing processes are applied for reaching highest efficiencies, in industrial fabrication, solely maskless stochastic etching processes are chosen. A prominent example are pyramidal textures on monocrystalline silicon (c-Si) realized by anisotropic wet chemical etching.[1] For multicrystalline silicon (mc-Si), isotropic acidic texturing is state of the art in industrial fabrication.[2] The resulting texture therefore can be homogeneous independent of crystal orientations; it is, however, inferior to pyramidal textures. For mc-Si, the gain in efficiency by applying a defined texture is especially pronounced. The so-called honeycomb texture was realized when efficiencies exceeding 20 percent were reached on this type of material for the first time.

However, this efficiency record was achieved using photolithographic processes. Therefore, their industrial-scale use is not economical. With the capability of originating micro- and nanostructures on areas of up to 1 square meter, interference lithography opens up interesting possibilities for the origination of micro- and nanostructures.[3,4] If this very demanding technology is combined with nanoimprint processes, an economically feasible process chain for the manufacture of photonic structures on large areas can be established.[5]

2. Structuring Technologies

2.1 Interference Lithography

For the definition of the exposure pattern in interference lithography, no mask is used, but a laser beam is split and the resulting coherent beams are expanded and then superimposed on a photoresist-coated sample. For the radiation source, we use an argon ion laser emitting at the UV wavelength of 363.8 nm. The resulting

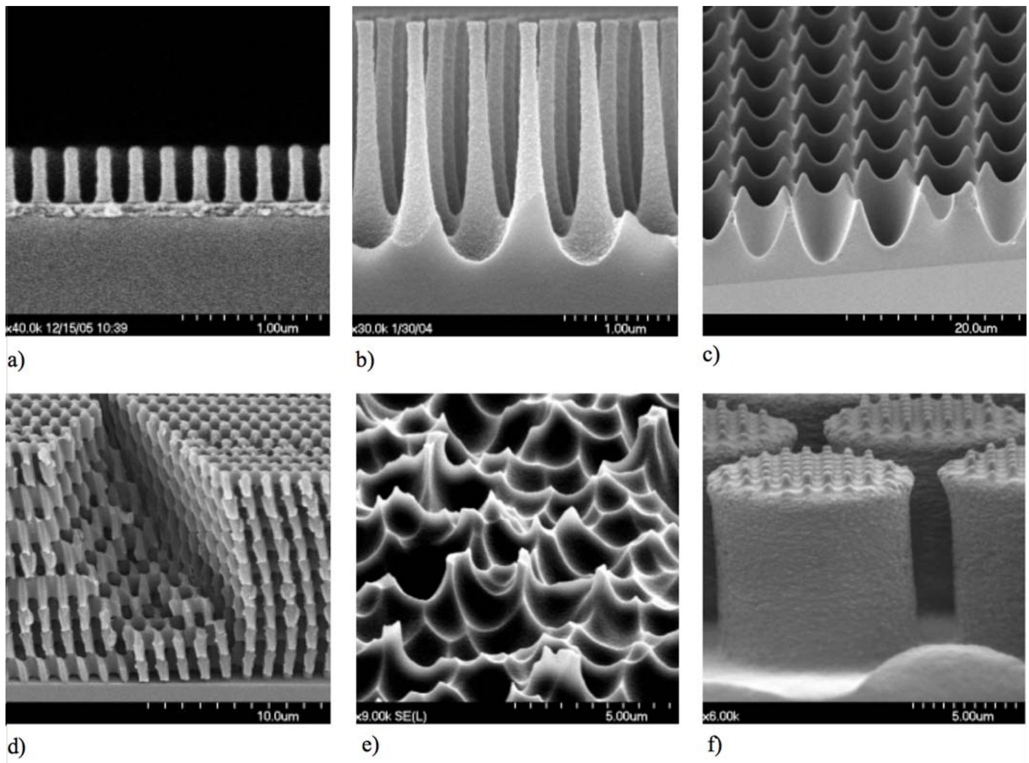

Figure 1 – Structures originated by interference lithography: a) linear grating (two wave interference); b) crossed grating with high aspect ratio (combination of two exposures, each with two waves); c) honeycomb structures (three wave interference); d) photonic crystal (four wave interference); e) surface-relief diffuser (multi-wave interference); f) combination structure for enhanced adhesion, inspired by the feet of geckos (three-wave interference plus double two-wave exposure)

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interference pattern is used to expose a photoresist-coated substrate, leading to a surface relief after a development step.

There are various ways to modify the exposure and to achieve complex structure geometries: The structure period can be adjusted; lamellar profiles, hexagonal geometries, 3D photonic crystal structures or aperiodic patterns can be originated by adapting angles of incidence and the number of interfering waves. An additional option is to combine different exposures in order to achieve an overlay of different structures.

So the strengths of interference lithography are a large variety of achievable structure types and profile shapes, structure dimensions reaching from 100 nm to 100 µm, and seamless structured areas up to 1.2 x 1.2 m^2 in a single exposure. To achieve this size, we use a vibration-isolated optical table system consisting of tables with 10 and 12 meters in length. To ensure high contrast exposures, the whole system needs to be kept extremely stable during exposure times of up to five hours. For an overview of achievable structures, see Figure 1.

The structures in photoresist – the so-called master structures – can serve as an etching mask for a pattern transfer, as a template for infiltration with different materials or they can be replicated via electroplating and subsequent replica-

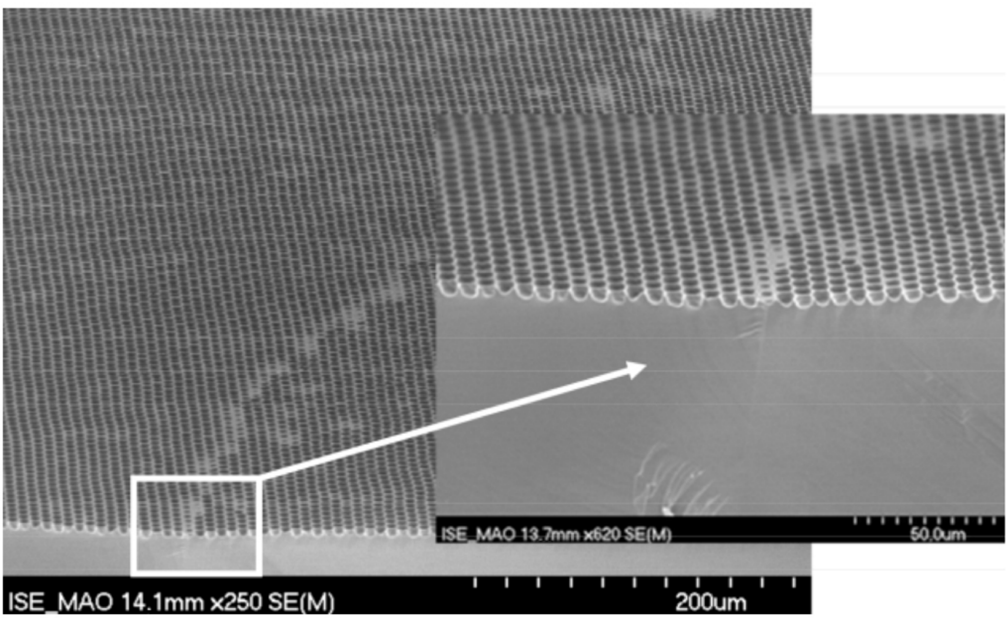

Figure 2 – Honeycomb textured mc-Si wafer after NIL and plasma etching. Shown is a magnification of a grain boundary.

tion processes such as nanoimprint lithography.

2.2 Nanoimprint Processes

Nanoimprint lithography (NIL) is a synonym for a process sequence in which a polymer layer is patterned in a hot embossing or a UV-replication process, and this patterned layer is then used as an etching mask to transfer defined patterns to a substrate underneath.[6] NIL processes have the potential to allow the fabrication of micro- and nanostructures on large areas in an industrially feasible way.

The master structures fabricated via interference lithography are used to replicate stamps for the nanoimprint process (this can be seen as preliminary process steps). As stamp materials, we use additional curing polydimethylsiloxane (PDMS) materials. These materials allow a non-wearing replication by cast-molding processes. The flexibility of these elastomeric stamps will later be required to obtain a conformal contact to surfaces that are not perfectly flat in the nanoimprint process.[7] Otherwise, full wafer imprinting would not be possible, and unwanted step-and-repeat processes would be necessary.

Having fabricated the stamps, the repetitive process steps for imprinting a resist layer follow. The PDMS stamp is pressed onto a resist-coated substrate, and while maintaining the pressure, a UV-exposure is conducted. The pressures applied during the imprint process are in the range of 0.1 to 0.6 bar. After the curing of the resist, the stamp must be de-molded, and the patterned layer remains on top of the substrate. To further increase the feasibility of the imprinting processes on an industrial scale, we are developing a roller-NIL tool. This tool allows the patterning of UV-curing resist layers on brittle, stiff and opaque substrates (e.g., silicon) in a continuous process flow. We are currently upscaling this tool to be able to pattern 156 x 156 mm^2 substrates.

3. Application Example: Honeycomb Front-Side Textures

The honeycomb texture was applied reaching the record efficiency of 20.4 percent on multicrystalline silicon (mc-Si).[8] Despite the obvious potential of this defined texture, an industrial realization was not possible due to the elaborate photolithography and related conditioning processes of the rough mc-Si substrates. We make use of NIL processes to fabricate this defined texture.

The complete process chain for this application begins with interference lithography to originate the hexagonal pattern of a period of 8 μm (Figure 1c). These master structures were fabricated on 250 x 250 mm^2 glass substrates. PDMS stamps are replicated from these master structures and are used for the NIL process later on. Using a planar stamp setup, etching masks on 100 x 100 mm^2 were patterned. After the patterning of the etching mask, the pattern transfer via etching follows. In this study, we used plasma etching processes for the pattern transfer; however, in the future, we will also report on wet chemical approaches for the etching of the honeycombs in combination with nanoimprint processes. This process chain is described more in detail in [9]. Figure 2 shows exemplary SEM micrographs of the resulting texture on a mc-Si wafer after the plasma etch-

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ing. In the resulting texture, a grain boundary is shown in two magnifications, indicating that there are minor problems due to steps at grain boundaries. However, it also can be seen that only a very small fraction of the patterned area is affected.

Honeycomb-textured substrates were then characterized by reflection measurements and were compared to standard references (planar, isotextured and inverted pyramid-textured substrates). The inverted pyramid was chosen as a reference system for being an upper bound for the quality of textures on silicon solar cells. The measurements were weighted with a photon flux corresponding to the AM 1.5.g spectrum to obtain an integrated weighted reflectance R_w. The measurements as well as values for R_w for all characterized substrates are shown in Figure 3. Note that there is a slight difference between the reflectivities of the resulting honeycomb texture on c-Si and on mc-Si. This results from inhomogeneities due to roughness as shown in Figure 2. However,

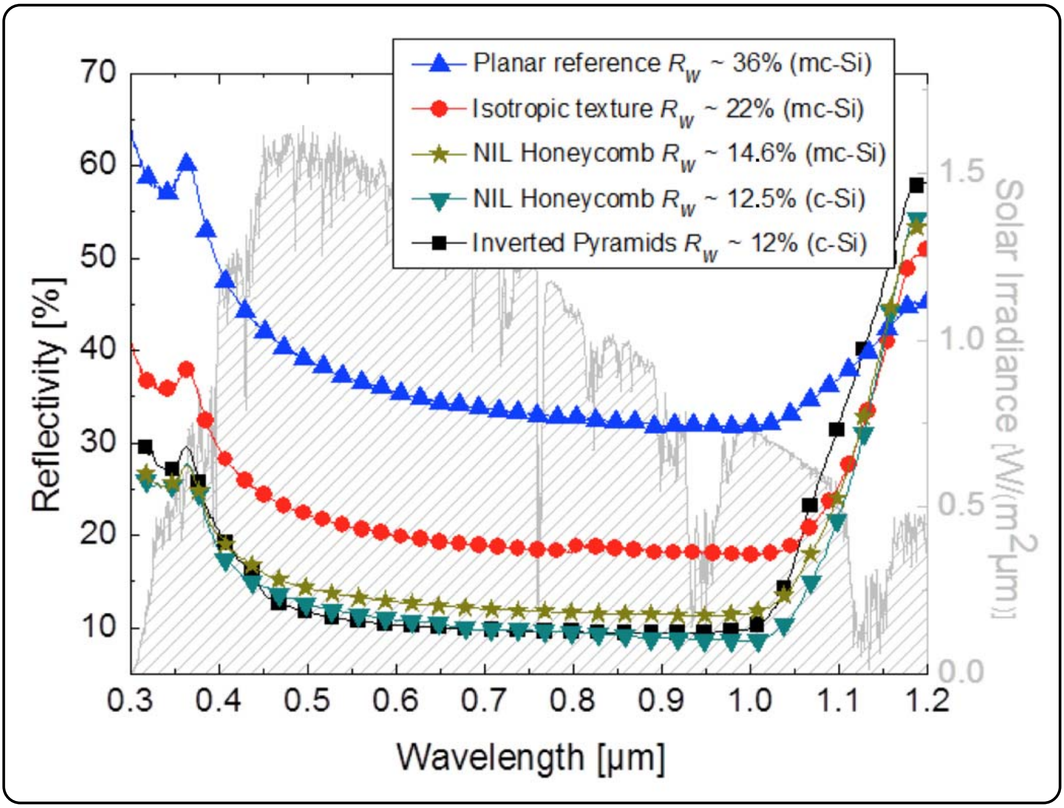

Figure 2 – Reflection measurements of differently textured substrates. The honeycomb texture realized by the presented process chain was characterized on c-Si as well as on mc-Si.[9]

the overall performance of the honeycomb texture realized by the presented process chain is excellent. On both types of substrates, the reflectance values are close to the high-efficiency inverted-pyramids texture on c-Si fabricated using photolithographic processes.

At the cell level, the high-efficiency potential of the textures realized by the presented process chain have already been demonstrated by short-circuit current densities exceeding 40 mA/cm^2 on FZ material.[10] As next steps, we will validate this high level of quality on mc-Si substrates. Furthermore, we are currently transferring all imprint processes to the roller-NIL tool we have developed. Using this tool, etching masks on 156 x 156 mm^2 substrates can already be patterned in a continuous process.

4. Conclusions and Outlook

Interference lithography and nanoimprint processes allow the fabrication of micro- and nanostructured surfaces on large areas in high throughput. As application, we demonstrated the honeycomb texturing of multicrystalline silicon. Initial results confirm the high-efficiency potential of the textures fabricated by the introduced process chain. However, the presented process chain is not just suitable for this mature concept; due to the very high resolution of the applied processes, they open up exciting possibilities for the future. Further concepts based on these processes are currently under investigation: diffractive back-side gratings for wafer-based solar cells, the realization of textured substrates for the TCO deposition in thin film applications or metal nanoparticle arrays for plasmonics.[5]

Acknowledgments

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