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Self-organized broadband light trapping in thin film amorphous silicon solar cells

C Martella, D Chiappe, P Delli Veneri, L V Mercaldo, I Usatii and F Buatier de Mongeot

1 Dipartimento di Fisica, Università di Genova, via Dodecaneso 33, I-16146 Genova, Italy
2 ENEA Portici Research Center, Piazzale E Fermi, I-80055 Portici (NA), Italy
E-mail: buatier@fisica.unige.it

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Abstract
Nanostructured glass substrates endowed with high aspect ratio one-dimensional corrugations are prepared by defocused ion beam erosion through a self-organized gold (Au) stencil mask. The shielding action of the stencil mask is amplified by co-deposition of gold atoms during ion bombardment. The resulting glass nanostructures enable broadband anti-reflection functionality and at the same time ensure a high efficiency for diffuse light scattering (Haze). It is demonstrated that the patterned glass substrates exhibit a better photon harvesting than the flat glass substrate in p–i–n type thin film a-Si:H solar cells.

1. Introduction
The use of textured interfaces and surfaces arranged with periodic, pseudo-periodic or random nanoscale surface patterns is under scrutiny in new nano-photonic components [1] or opto-electronic devices (light-emitting diodes, solar cells, etc) featuring light trapping and photon harvesting [1–4]. In surfaces endowed with high aspect ratio subwavelength features a progressive transition of the refractive index from the value of air to that of the substrate confers bio-mimetic broadband anti-reflection functionality analogous to that observed in the corneas of nocturnal moths [5, 6]. Large angle photon scattering is instead induced by surface corrugations with lateral size comparable or bigger than light wavelength [7, 8]. The combination of these two effects thus appears a promising approach to broadband photon harvesting in thin film solar cells [9–12]. In this context, nano-fabrication techniques that ensure patterning of a broad range of materials over macroscopic areas in a cost effective way are required and those based on self-assembly are among the most appealing. Low energy ion beam sputtering (IBS) has been successfully employed in several seminal works aiming at nanopatterning and functionalizing the surface of technologically relevant materials over large areas [13–15]. However, as observed in the case of several amorphous or semiconductor substrates, due to the prevailing action of smoothing mechanisms, direct ion irradiation does not always lead to an efficient kinetic evolution of the surface pattern [16–18].

Recently we have demonstrated that self-organized ion beam sputtering (IBS) assisted by a metal nanowire stencil mask allows the formation of high aspect ratio surface features on glass [19] and GaAs [20] substrates, which would otherwise show a slow kinetic evolution of the pattern when directly irradiated. During the first stages of ion irradiation the sacrificial metal film self-organizes into a nanowire array which, at higher ion fluencies, performs like a lithographic stencil mask that allows selective etching of the underlying substrate [19, 20]. Here we propose a novel version of the process in which the life of the metallic mask is extended by means of a ‘co-deposition’ from an auxiliary Au atom source, thus further enhancing the vertical dynamic of the surface pattern etched into the underlying substrate. The high aspect ratio features confer broadband anti-reflection functionality to the textured glass substrate and at the same ensure a high efficiency for diffuse scattering (Haze) [7, 8], in analogy to the observations made for bio-mimetic interfaces [5, 6]. In order to demonstrate the potentiality of the patterned glass...
substrates in promoting photon harvesting, here we compare the performance of thin film amorphous silicon solar cells grown on the nanostructured glass templates with that of devices grown on reference flat glasses.

2. Experimental details

Polycrystalline Au films with a thickness of 150 nm have been evaporated under UHV conditions from an alumina crucible on a flat borosilicate glass substrate (average grain diameter around 100 nm and RMS surface roughness around 2 nm) [21, 22]. The samples have been subsequently exposed to defocused ion beam irradiation from a gridded multiaperture Ar$^+$ source (Tecra instruments) under grazing incidence conditions ($\theta = 82^\circ$), constant flux of $4.0 \times 10^{15}$ ions cm$^{-2}$ s$^{-1}$ (measured in a plane orthogonal to the beam direction) and energy of 800 eV. A biased tungsten filament ($V_{\text{bias}} = -13$ V), providing electrons via thermionic emission, was placed close to the extraction grid in order to compensate surface charging effects due to ion irradiation.

The morphology of the samples has been investigated ex situ by means of atomic force microscopy (AFM) operating in intermittent-contact mode (Nanosurf Mobile S) equipped with a high aspect ratio Si tip (ACLA by AppNano). The topography images have been numerically analyzed in order to quantitatively evaluate the surface RMS roughness, the one-dimensional power spectral density functions (1D-PSD) and the height–height correlation functions, $H_{\text{cf}}(r)$ [23].

In order to evidence the anti-reflective and scattering properties induced by the surface nanostructures, we performed far field optical reflectivity measurements by means of an integrating sphere (Ocean Optics ISP-50-8-R) fiber coupled to a compensated deuterium–halogen lamp (DH-2000-BAL, Mikropak) and to a high resolution solid state spectrometer (HR4000 Ocean Optics). All spectra have been normalized to the integrated reflectance signal of the standard reference sample (RS2-Avantes, Al + MgF coating).

To evidence the potentiality of the patterned glass as textured support for thin film solar cells, two identical amorphous silicon p–i–n single junctions have been fabricated in the same run both on nanostructured and on flat glass substrates for a meaningful comparison of the performances. As front transparent electrode, a 750 nm-thick Al-doped ZnO layer has been deposited by RF magnetron sputtering. The ZnO films conformally grown on the textured glass substrates are characterized by high optical transmission (about 80%) and low sheet resistance ($\approx 10$ $\Omega/\square$). The p–i–n structure consists of a 7 nm-thick amorphous silicon-carbide p-layer, a 350 nm-thick amorphous silicon i-layer, and a 30 nm-thick microcrystalline silicon n-layer. Fabrication details of the thin film solar cells grown by plasma enhanced chemical vapor deposition (PE-CVD) are reported elsewhere [24]. For both substrates, 0.3 cm$^2$ Ag pads have been finally evaporated as back contacts. The devices have been characterized by measuring the current–voltage ($I–V$) characteristic with a dual lamp solar simulator in standard test conditions (25°C, AM1.5 g, 1000 W m$^{-2}$) and the external quantum efficiency (EQE).

3. Results and discussion

Following ion bombardment, as evidenced in the AFM topography of figure 1(a), the surface morphology of the polycrystalline Au film gradually transforms into an undulated ripple; at a fluence $F_1 = 3 \times 10^{18}$ ions cm$^{-2}$, due to ion erosion the bottom of the valleys reaches the glass substrate and the undulated pattern decomposes into an array of Au nanowires [19]. The strongly anisotropic nanowires are elongated along the ion beam projection (black arrows in the panels) and reach the length of several micrometers, the vertical range of the image amounts to 88 nm corresponding to an RMS roughness $\sigma$ of about 10.9 nm. The metal nanowire array can be considered as a stencil mask which selectively guides ion erosion of the underlying substrate in correspondence to the gaps which separate the nanowires. In figure 1(b) we show the morphology of the glass substrate after protracting ion bombardment up to fluence $F_2(5 \times 10^{18}$ ions cm$^{-2}$). The metal mask is now completely etched and its pattern propagates with a vertical amplification into the glass substrate. We can notice that the vertical range now reaches 144 nm corresponding to an RMS roughness of 25 nm.

In order to achieve anti-reflection functionality the vertical amplitude of the glass surface corrugations must be further increased up to a significant fraction of light wavelength [5, 6]. For this purpose we developed a co-deposition procedure in which, at fluence $F_1$, the auxiliary Au source is reactivated concurrently to ion bombardment in order to deposit Au atoms at a flux comparable with the measured erosion rate of the metal ($\approx 1.3$ nm min$^{-1}$) [20]. Due to incorporation of the incoming gold atoms into the nanowires, we have been able to protract their life, thus eroding deeper valleys in the glass substrate. After an additional ion fluence of $3.6 \times 10^{18}$ ions cm$^{-2}$ the Au flux was stopped and the sputtering prolonged until complete removal of the residual metal nanowires. Figure 1(c) shows the topography of the glass substrate at the end of the co-deposition process at room temperature (total fluence $F_{\text{III}} = 1 \times 10^{19}$ ions cm$^{-2}$) and evidences a further amplification of the vertical range which increases to 248 nm (RMS roughness 34 nm). One of the factors which limit the effectiveness of the co-deposition assisted procedure is related to sputtering and removal of the gold adatoms which landed in the glass valleys, before they got incorporated into the metal nanowires. In order to speed-up thermally activated diffusion of the Au atoms from the glass valleys towards the nanowires, a further co-deposition experiment was performed at an increased temperature of 700 K. The effectiveness of the process is demonstrated by the AFM topography of figure 1(d) which, in comparison to figure 1(b), evidences a remarkable increase of the vertical range from 144 to 440 nm and of the RMS roughness from 25 to 83 nm.

By direct visual inspection of the AFM topographies shown in figure 1 we can qualitatively notice that also the lateral size of the features has increased. We thus analyzed quantitatively the evolution of the pattern morphology in the framework of dynamic scaling theories [23, 25–27] by
evaluating the height–height correlation function \( H_d(r) = \langle [h(x + r) - h(x)]^2 \rangle \) where \( h(x) \) is the surface height profile acquired along the fast scan direction of the AFM pattern and \( h(x + r) \) is the surface height profile evaluated in a position shifted by \( r \). The square of the difference of the two shifted height profiles is then averaged over the running variable \( x \). The \( H_d(r) \) functions shown in figure 2(a) were calculated by cumulating and averaging the one-dimensional topographic line profiles, \( h(x) \), acquired along the fast scan direction in correspondence to the different AFM morphologies of figures 1(a)–(d). According to dynamic scaling theories for small values of the displacement \( r \), \( H_d(r) \) follows a power law \( H_d(r) \sim r^{2\alpha} \) where \( \alpha \) is the ‘roughness’ exponent (linear trend in log–log scale), while for large displacement values \( H_d(r) \) tends to a saturation value \( 2\sigma^2 \) where \( \sigma \) is the RMS roughness [23, 26]. The asymptotic break between the two regimes of \( H_d(r) \) allows to determine the ‘lateral correlation length’, \( \xi \), i.e. the distance \( r \) within which the surface height fluctuations are correlated. For distances \( r \gg \xi \), the height variations are instead spread randomly [23, 26]. The correlation length of the rippled Au film at fluence \( F_I \) (bottom gray trace, corresponding to the morphology of panel 1(a)) amounts to \( \xi = 100 \pm 10 \) nm, a figure comparable to the mean size of the metal grains, which represents the maximum lateral range of diffusive relaxation processes during ion beam sputtering of the polycrystalline metal film [21, 22]. At fluence \( F_{II} \) (black trace, corresponding to the morphology of panel 1(b)), complete erosion of the Au mask has occurred and \( \xi \) slightly increases to \( 115 \pm 11 \) nm. For co-deposition at room temperature, red trace corresponding to the morphology of panel 1(c), \( \xi \) increases to \( 120 \pm 12 \) nm due to the longer range of glass relaxation mechanisms which are responsible for the coarsening of small scale spatial modulations (thermally activated and ballistic diffusion, re-deposition effects, surface viscous flow, etc) [19, 20]. The importance of thermally activated diffusive relaxation in determining coarsening of the glass modulations is confirmed by the large increase of \( \xi \) to \( 214 \pm 21 \) nm in the co-deposition experiment performed at 700 K, blue trace corresponding to the morphology of panel 1(d).

In order to better evidence the vertical amplification of the specific spatial components we calculated the one-dimensional power spectral density (1D-PSD) functions \( g(q) \) corresponding to each of the AFM topographies of figures 1(a)–(d). The \( g(q) \) traces are plotted in figure 2(b) adopting the same order from bottom to top chosen for the height–height correlation function \( H_d(r) \) in panel 2(a). Since the area subtended by every PSD curve is proportional to the surface RMS roughness, the \( g(q) \) traces demonstrate that maximum amplification of the glass pattern is achieved when co-deposition is performed at high temperature (top blue trace corresponding to the morphology of panel 1(d)).

Figure 1. AFM images of (a) Au film sputtered at \( \theta = 82^\circ \) and fluence \( F_I = 3 \times 10^{18} \) ions \( \text{cm}^{-2} \). Vertical range 88 nm, \( \sigma = 10.9 \) nm. (b) Glass surface after complete erosion of the Au mask, fluence \( F_{II} = 5 \times 10^{18} \) ions \( \text{cm}^{-2} \). Vertical range 144 nm, \( \sigma = 25 \) nm. (c) Glass surface at the end of co-deposition experiment at room temperature, total fluence \( F_{III} = 1 \times 10^{19} \) ions \( \text{cm}^{-2} \). Vertical range 248 nm, \( \sigma = 34 \) nm. (d) Glass surface after a co-deposition experiment at 700 K, total fluence \( F_{IV} = 1 \times 10^{19} \) ions \( \text{cm}^{-2} \). Vertical range 440 nm, \( \sigma = 83 \) nm. The scale bars in the images are 1 \( \mu \text{m} \), the black arrows indicate the ion beam projection.
For a quantitative demonstration of the potential of ion beam nanopatterning assisted by co-deposition, we can normalize the 1D-PSD power spectral density of the patterned glasses $g_i(q)$ to the 1D-PSD function of the patterned gold stencil mask $g_1(q)$ (bottom gray trace in panel 2(b), ion fluence $F_i$) thus defining the amplification factor $H_i(q) = (g_i(q)/g_1(q))^{1/2}$ as described in [19]. In this way, as plotted in figure 2(c), it is possible to quantitatively evidence the amplification of each harmonic component of wavevector $q = 1/\lambda$; the bottom (black) trace corresponds to the glass after fluence $F_i$; the middle trace (red) and the top trace (blue) are relative to the co-deposition experiments at room and high temperature respectively. In the limit of large wavevectors, $H_i(q)$ is stable around 1 (no net amplification) independently from the nanopatterning process employed, indicating that for spatial wavelengths below 100 nm diffusive relaxation and ion erosion compensate each other. For larger spatial wavelengths above 100 nm (smaller values of $q$) the amplification turns out to depend strongly on the patterning process: in absence of co-deposition, an almost constant value around 3 is obtained while for co-deposition at room temperature the amplification factor varies from 4 to 6. Remarkably, in the co-deposition experiment at high temperatures, $H_i(q)$ of the spatial wavelengths in the range above 800 nm rapidly increases from 5 towards 10 as a result of the shielding action of the stencil mask which is protracted in the presence of thermally activated mass transport of Au atoms.

In figure 3(a) we study the total optical reflectance in the vis–NIR range (400–900 nm) of the flat reference glass substrate (top black trace); the spectrum of a sample patterned by the stencil mask without co-deposition, corresponding to the morphology of panel 1(a), (black trace) patterned glass at fluence $F_{i0}$ corresponding to panel 1(b), (red trace) glass patterned by co-deposition at room temperature at fluence $F_{i0}$ corresponding to panel 1(c), (blue trace) glass patterned by co-deposition at 700 K at fluence $F_{i0}$ corresponding to panel 1(d). (b) Log–log plot of 1D-PSD functions $g_\lambda(q)$. The traces are plotted in the same order and colors of panel 2(a). (c) Semi-Log plot of the transfer function $H(q)$ describing the vertical amplification of the spatial components normalized to the patterned Au mask at fluence $F_1$. The traces are plotted in the same order and colors of panel 2(a) and 2(b).

![Figure 2.](image-url)

For a quantitative demonstration of the potential of ion beam nanopatterning assisted by co-deposition, we can normalize the 1D-PSD power spectral density of the patterned glasses $g_i(q)$ to the 1D-PSD function of the patterned gold stencil mask $g_1(q)$ (bottom gray trace in panel 2(b), ion fluence $F_i$) thus defining the amplification factor $H_i(q) = (g_i(q)/g_1(q))^{1/2}$ as described in [19]. In this way, as plotted in figure 2(c), it is possible to quantitatively evidence the amplification of each harmonic component of wavevector $q = 1/\lambda$; the bottom (black) trace corresponds to the glass after fluence $F_i$; the middle trace (red) and the top trace (blue) are relative to the co-deposition experiments at room and high temperature respectively. In the limit of large wavevectors, $H_i(q)$ is stable around 1 (no net amplification) independently from the nanopatterning process employed, indicating that for spatial wavelengths below 100 nm diffusive relaxation and ion erosion compensate each other. For larger spatial wavelengths above 100 nm (smaller values of $q$) the amplification turns out to depend strongly on the patterning process: in absence of co-deposition, an almost constant value around 3 is obtained while for co-deposition at room temperature the amplification factor varies from 4 to 6. Remarkably, in the co-deposition experiment at high temperatures, $H_i(q)$ of the spatial wavelengths in the range above 800 nm rapidly increases from 5 towards 10 as a result of the shielding action of the stencil mask which is protracted in the presence of thermally activated mass transport of Au atoms.

Following the approach of [28, 29] we now attempt a quantitative comparison between the diffraction properties of the self-organized broadband gratings with those of sinusoidal gratings. In this simple context the surface morphology determined from the AFM pattern has been approximated by a one-dimensional sinusoidal grating with period ($P$) and amplitude ($h$) related to the experimental correlation length, $\xi$, and the RMS roughness, $\sigma$, by $h = \sigma 2^{1/2}$ and $P = \pi \xi 2^{1/2}$. The calculation of the total reflectivity of the sinusoidal grating has been performed within a rigorous coupled wave analysis (RCWA) approach implemented in the Matlab software package GD-CALC (Grating Diffraction Coupled Wave Analysis).
when the roughness of the model sample is increased to co-deposition at room temperature (figure 1(c)). Conversely, co-deposition (figure 1(b)) and for the sample prepared with both the sample prepared by stencil mask without substrate over the whole spectral range: this condition holds unchanged with respect to that of the flat reference black circles) indicate that the reflectivity remains essentially σ <

relative to morphology with a reduced RMS roughness simplifying assumptions of the model, the calculations account multiple reflections at interfaces.

flat substrate, measured at normal incidence and taking into been evaluated from the Fresnel reflection coefficient of a sphere setup, a monochromatic unpolarized plane wave at an incident angle of 8◦ with respect to the substrate normal is set as the light source. The refractive index of glass has central value of 214 nm. Analogously to the experimental configuration adopted for the measurements in the integrating sphere setup, a monochromatic unpolarized plane wave at an incident angle of 8° with respect to the substrate normal is set as the light source. The refractive index of glass has been evaluated from the Fresnel reflection coefficient of a flat substrate, measured at normal incidence and taking into account multiple reflections at interfaces.

As shown in figure 3(a), despite the rather strong simplifying assumptions of the model, the calculations relative to morphology with a reduced RMS roughness σ < 40 nm and a correlation length of 214 nm (open black circles) indicate that the reflectivity remains essentially unchanged with respect to that of the flat reference substrate over the whole spectral range: this condition holds for both the sample prepared by stencil mask without co-deposition (figure 1(b)) and for the sample prepared with co-deposition at room temperature (figure 1(c)). Conversely, when the roughness of the model sample is increased to a value σ = 83 nm, equivalent to that of the sample of figure 1(d) prepared by high temperature co-deposition, the calculated total reflectance (open symbols) reaches an almost quantitative agreement with the measured data, following the observed 10–20% drop. Due to the simplifying assumptions of the model which assumes an almost monodisperse grating morphology, quantitative agreement is found above 700 nm, while it slightly underestimates reflectance for lower wavelengths.

We can rationalize these observations by taking into account that reflection of light from a rough surface may be affected both by the RMS roughness and by the spatial correlation length of the surface features. Reduction of light reflection by index grading (‘moth eye’ effect [5]) can in fact be achieved when the refractive index of substrate and air are gradually matched by high aspect ratio corrugations whose amplitude is a significant fraction of the wavelength of incident light and whose lateral periodicity is below the diffraction limit. For larger scale spatial corrugations instead, the reflected and transmitted intensity can be also redistributed from the specular to the diffracted components, thus increasing large angle diffuse scattering [8, 12, 31, 32].

In view of applications of the patterned interfaces in thin film photovoltaic devices featuring enhanced light trapping, either in the front or in the back layers, we stress that the diffraction efficiency of the nanostructured interfaces can be of predominant importance with respect to their anti-reflection behavior: increased light absorption can in fact be promoted when photons are trapped and waveguided in the thin absorber layer by total internal reflection occurring at large scattering angles [11]. In order to experimentally evaluate the scattering efficiency of the surface pattern of figure 1(d), formed by co-deposition at high temperature, we measured its diffuse reflectance excluding the specular component of the reflected light beam by means of an absorbing trap within the integrating sphere. In figure 3(c) we show the ratio between diffuse and total reflected light (Haze): as one can notice, a significant Haze of 60% is measured at λ = 400 nm while it decreases to 30% at λ = 900 nm. Such a behavior can be interpreted considering that for shorter light wavelengths diffuse scattering by the corrugations of the pattern is more efficient, while for light wavelengths longer than the typical lateral scale of the corrugations the grating diffraction condition is not satisfied and light reflection (transmission) takes predominantly place in the specular (direct) component [11]. In terms of photocurrent enhancement, a high Haze value can thus compensate a relatively small reduction of the integrated reflectance since, due to scattering at the rough interfaces, the average photon path length in the absorber layer is increased. Additionally, one must also consider that in a thin film solar cell conformally grown on the nanostructured glass substrate, textured interfaces are also introduced between materials with a more pronounced dielectric contrast than that of the glass/air couple investigated here (e.g. glass/ZnO:Al and ZnO:Al/Si); stronger variations in the reflectivity and in the scattering properties of these high refractive index interfaces are thus expected after nanopatterning.

![Figure 3](image_url)

**Figure 3.** (a) Measured integrated reflectance spectra of the reference flat glass substrate (top black trace) and of the patterned glass substrate of figure 1(d) (bottom blue trace). The simulated reflectance spectra calculated according to the RCWA model are also plotted for the flat reference glass (open black circles), and for the patterned glass (blue open triangles). (b) Measured normalized diffuse reflectance (Haze) of the patterned surface of figure 1(d).

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Figure 4. Current–voltage characteristic (a) and external quantum efficiency (b) of identical amorphous silicon p–i–n solar cells deposited on nanostructured (red line) and flat (black line) glass substrate. The short-circuit current density reported in the legend in panel (b) has been calculated for both solar cells from the EQE curves by convolution with the photon flux of the global air mass 1.5 solar spectrum.

In order to test the potentiality of the nanostructured glass substrates in view of photon harvesting applications, we have grown two identical amorphous thin film silicon p–i–n single junction) supported on patterned and flat templates, as discussed in the experimental section. From the I–V characteristic (figure 4(a)) similar values of Fill Factor (about 60%) and open circuit voltage (about 0.8 V) have been obtained with both substrates. The short-circuit current density \( J_{SC} \) of the solar cells has been calculated from the EQE curves by convolution with the photon flux of the global air mass 1.5 solar spectrum. The comparison between the spectral responses measured with the two substrates is shown in figure 4(b). The EQE of the cell grown on the nanopatterned substrate (upper red trace) is higher in comparison to that of the flat reference substrate (lower black trace) over the whole spectral range. The significant relative enhancement of EQE, in the order of 15%, indicates a corresponding increase in photocurrent with respect to the flat substrate. Quantitatively, \( J_{SC} \) increases from 12.3 mA cm\(^{-2}\) evaluated for the flat glass to 14.2 mA cm\(^{-2}\) for the nanostructured one. In particular, the significant EQE improvement in the long wavelength range is indicative of an efficient light trapping that determines multiple passes of scattered light within the solar cell, while the reduction of the fringes caused by interference phenomena is due to scattering from the uncorrelated roughness of the patterned substrate. According to [11] we also mention the possibility that higher diffracted orders, scattered from the one-dimensional modulation, are trapped by total internal reflection as waveguided modes and confined within the high refractive index layer. All these effects, in combination with the slight reduction of the reflection losses at interfaces, are expected to contribute to the overall enhancement of the photon conversion efficiency of about 1% absolute.

In closing we stress that the self-organized nanopatterning approach, demonstrated here employing gold nanowire stencil masks endowed with low electrical conductivity [33, 34], is potentially scalable to lower cost metals like e.g. Ag, Pt, Cu, Co, Fe, Ni which are prone to forming ripples under similar ion beam sputtering conditions [22, 35–37]. The interest in the use of the gold nanowire stencil masks is also related to perspective future developments aiming at photon harvesting in which the localized plasmon resonances supported on the gold nanowires could be exploited to enhance light scattering in the absorber layer [38, 39].

4. Conclusion

In conclusion we have demonstrated a novel approach to inducing the self-organized formation of high aspect ratio nanoscale features on glass substrates. The patterned glass surfaces exhibit a broadband reduction of the reflection losses, and a high degree of light scattering (Haze) in the NIR–vis range. The process is based on selective ion erosion through the gaps of a self-organized gold stencil mask formed by defocused ion beam sputtering. The high aspect ratio features are formed only when ion erosion takes place concurrently to co-deposition of gold metal atoms from an auxiliary evaporation source at high substrate temperatures. Amorphous Si thin film solar cells grown on the textured substrates show a remarkable improvement of the spectral response with respect to the reference devices grown on unstructured glass substrates. Enhancement of external quantum efficiency (EQE) over the full spectral range is observed, with a short-circuit current density improvement in the order of 15%. This result proves the strong potential of our approach for producing nanopatterned substrates for efficient photon harvesting in thin film solar cells.

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