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学位授与年月日	2014-03-24
URL	http://doi.org/10.15083/00006817

論 文 の 内 容 の 要 旨

論文題目　Maskless plasma etching antireflection nanostructures on optical elements in concentrator photovoltaic systems
（集光型太陽光発電システムにおけるマスクレス・プラズマエッチング・ナノ構造を用いた低反射光学素子）

氏　　名　　タマヨ ルイス　エフライン エドアルド

Concentrator photovoltaic (CPV) systems are a potential candidate to achieve low cost solar energy because in these systems the solar cell efficiency increases with concentration and the amount of semiconductor material required is lower. CPV systems use Fresnel lenses to focus the light into homogenizers, which uniformize the flux distribution incident to the subjacent solar cell and does other optical corrections. A disadvantage of these optical elements is that they create three optical interfaces that reflect the incident light and together account for about 12% of losses. To achieve higher efficiency in CPV systems, these losses need to be reduced. These optical interfaces can be curved or corrugated, which limits the applicability of traditional antireflection methods. In addition, the antireflection effect should be broadband because the solar cell placed below the homogenizer absorbs most of the solar spectrum. Finally, the fabrication methods need to be applicable in large areas and to be cost effective. For these reasons, maskless plasma etching processes were selected to texture the PMMA (Fresnel lens) and glass (homogenizer) interfaces and were studied in this thesis. An additional problem in CPV systems is the dew condensation on the front and back side of the Fresnel lenses. To solve this problem, a hydrophobic coating on nanostructured surface was evaluated on the back side of a Fresnel lens.

In chapter 1, the basics of solar energy, CPV systems, and the motivation and outlines are introduced. In chapter 2, the approaches employed to study and solve the above mentioned problems are described. Also, the CPV system studied is introduced along with numerical calculations of optimum nanostructures.

Chapter 3 is focused on the fabrication methods employed to fabricate broadband antireflection nanostructures on glass and on PMMA. On the surface of Schott B270 glass substrates, a CHF_3 plasma etching process achieving the fabrication of high aspect ratio nanostructures was developed. The O_2 plasma etching and water rinsing were applied as cleaning processes afterwards. Broadband high transmittance was achieved on Schott B270 glass substrates, reaching nearly 96% and over 99% on samples with one and both treated sides, respectively. This improvement resulted from the formation of tapered high aspect ratio nanostructures enhanced by graded material distributions created by the selective etching of Si and the concentration of Ca_xF_y at the tips of the nanostructures during CHF_3 plasma etching. The aspect ratio increased with increasing the CHF_3 plasma etching process time. In B270, the formation of high aspect ratio nanostructures was achieved without lithography or the assistance of any deposited mask, making it a novel fabrication method and suitable for curved and large surfaces. The surface of various types of glasses and quartz substrates were treated using the same processes obtaining antireflection or scattering properties. The antireflection effect depended on the size and aspect ratio of the nanostructures. Scattering appeared when fabrication of large structures on the surface was obtained. Surface and cross section composition measurements revealed that the glass composition plays a critical role to obtain antireflection or scattering structures. FDTD and RCWA simulations were carried out to study the morphology and graded composition effects. At the Fraunhofer IOF, two types of processes were applied on PMMA substrates and LPI's Fresnel lenses. The first one (S1) uses a self-generated mask formed during O_2 and Ar plasma etching. The second type (S2) uses a TiO_2 thin layer prior to the same process as in S1. Depending on the fabrication process, two types of antireflection structures were generated and applied on one-side and both-sides of PMMA substrates and Fresnel lenses.

In chapter 4, the optical and field tests evaluation of Fresnel lenses and homogenizers with nanostructured surfaces are presented. Module assembly and field tests were carried out in Madrid at LPI-CeDint facilities. The current-voltage curves were measured for each sample and the efficiencies were calculated. Spectrolab's concentrator cell assemblies (CCAs) using triple junction solar cell GaInP (1.88 eV) / GaInAs (1.41 eV) / Ge (0.67 eV) were encapsulated below the treated homogenizers and a reference Fresnel lens was used to evaluate the effect of the glass nanostructuring process, which achieved maximum 3.78% and 2.75% J_{sc} and efficiency relative gains, respectively. To evaluate the effect of the nanostructures on the Fresnel lenses, the same bare secondary optical element and Spectrolab CCAs were employed. On the Fresnel lens with S2 on both sides, maximum 6.56% and 3.82% J_{sc} and efficiency relative gains were obtained, respectively. The efficiency relative gains were lower than the J_{sc} ones because the Fill Factor (FF) was degraded on the textured samples. The origin of the FF decrease is under consideration, but it was found that the bottom cell does not become limiting when employing the antireflection nanostructures. The modification of the spectral or irradiance homogeneity on the sub-cells is a possible cause. An additional possibility is that the additional generated current overheats the solar cell, hence reducing the FF. V_{oc} remained unchanged; J_{sc} was normalized at

Direct Normal Irradiation 900 W/m^2 and the efficiency at 25°C. The hydrophobic coating was successfully fabricated on the back side of the Fresnel lens, but the FF significantly decreased in this case.

In chapter 5, applications of nanostructured glass or PMMA surfaces are introduced to flat PV. Also the applications to space cover glasses and aspheric lenses were demonstrated. Finally, in chapter 6 the conclusions and outlines of this thesis are presented.