

# Bio-inspired Broadband and Omni-directional Antireflective Surface based on Semiconductor Nanorods

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**Abstract:** Bio-inspired layers of semiconductor nanorods increase light coupling into a high refractive index substrate. Reflection and transmission measurements show unambiguously, that the reduced reflection is due to optical impedance matching at the interfaces.

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## 1. Introduction

Antireflection surfaces play an important role for enhancing light coupling into solar cells. Antireflective layers can be classified into two different types: I) homogeneous layers or step index layers and II) inhomogeneous layers or graded index layers [1]. Homogeneous layers, or step-index layers, reduce the reflection due to destructive interference of light reflected at different interfaces. While the fabrication of single antireflection layers is well known for decades, the layer thickness and material have to be chosen carefully for each wavelength, angle, and substrate. In contrast to step index layers, graded refractive index layers reduce the reflection due to a gradually increasing refractive index which leads to optical impedance matching at the interfaces and therefore does not allow for reflections. Theoretically, a drastic reduction of the reflection for angles up to 80° and for a wide spectral range is possible. While it was known that graded refractive index coatings can reduce the reflection and therewith improve the light coupling efficiency into high index materials, fabrication of layers with a refractive index close to the refractive index of air remained challenging, i.e. a refractive index of 1. A solid material that matches a refractive index of 1 is needed, when the substrate is surrounded by air and obviously, the refractive index of any dense solid material is too large.

Since Bernhard reported in 1967 that the eyes of moths are covered with nanostructures that improve the light incoupling [2], the effect of these nanostructures has been investigated theoretically [3]. Nanostructures improve the light coupling into the eyes of moths by forming a layer with graded refractive index varying from 1 at the air-nanostructure interface to the refractive index of the eye. Nowadays, nanostructuring techniques allow fabrication of bio-inspired subwavelength structures which exhibit a very low effective refractive index when packed densely together [4-5]. While these structures possess very low values for specular reflection, it is not clear whether this reduced reflection is due to a graded-refractive index, due to absorption or due to scattering in the layer.

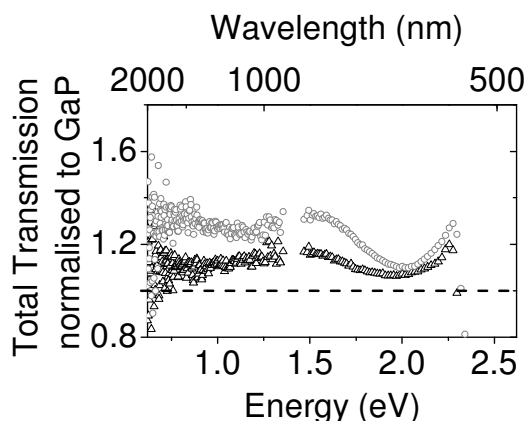
Here, we unambiguously demonstrate by measuring the transmission and reflection of bio-inspired GaP nanorods on top of a GaP substrate that the reduction of the reflection in these layers is mainly caused by a graded-refractive-index coating and interference in the nanorod film, and that the role of scattering losses and absorption by the nanorod layer is secondary [6]. We have chosen to work with GaP nanorods grown on GaP substrates, because GaP is transparent in the red and near infrared and therewith allows for measuring transmission. However, nanorods can be grown using several group IV, III/V, or II/VI semiconductors and can be grown heteroepitaxially, allowing for growth of non-absorbing antireflection layers on top of any semiconductor material used for solar cell applications.

## 2. Experiments

For investigating the antireflective properties of nanorod layers, we have fabricated conically shaped and cylindrical nanorods by bottom-up processing. GaP nanowires are grown using the vapour-liquid solid (VLS) growth mechanism by metal-organic vapor phase epitaxy (MOVPE) on a GaP substrate. In ensembles of conically shaped nanorods, a graded refractive index can be achieved with a low effective refractive index at the top and a high effective index at the bottom, due to the variation of the filling fraction of GaP along the growth direction of the rods. The cylindrical nanorods show an antireflection behavior, due to a distribution of nanorod lengths that leads to a reduced density toward the top of the layer.

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We performed angle-integrated transmission and reflection measurements using an integrating sphere to measure the zero-order transmitted or reflected beam as well as the diffusely transmitted or reflected light simultaneously. Fig. 1 shows the total transmission of the conically shaped nanorods and the cylindrical nanorods normalized to the total transmission through a bare GaP substrate: For photon energies from 0.62 eV to 2.26 eV, the transmission is increased for both samples with respect to the bare GaP substrate. The sharp absorption edge visible at 2.26 eV is due to the electronic bandgap of GaP. In agreement with the total transmission measurement, the total reflection is reduced over the whole energy range measured.



**Fig. 1.** Total transmission of conically shaped GaP nanorods (gray circles) and cylindrical GaP nanorods (black triangles) grown on a GaP substrate (black triangles) normalized to the transmission of a bare GaP substrate. The dashed line indicates a value of 1, corresponding to the bare GaP substrate.

We have performed calculations of the transmission and reflection using the transfer-matrix method and by fitting the measurements, we found that the reduction of the reflection and the increase in transmission is indeed due to a graded-refractive index in the nanowire layer.

Further, measurements of the zeroth-order transmission and reflection of a layer of cylindrical nanorods for angles of incidence up to  $60^\circ$  showed an increase in transmission and a corresponding reduction in reflection over the whole angular range compared to a bulk GaP substrate, showing that the nanorod layer forms an omnidirectional antireflective layer.

### 3. Conclusions

We have investigated the antireflective properties of layers of GaP nanorods using angle-integrated and angle-resolved wavelength dependent transmission and reflection measurements. Experimentally, we have fabricated nanorods by chemical vapor deposition using the vapour-liquid-solid mechanism. We have shown that the increased transmission and corresponding reduced reflection of these layers is related to a graded refractive index in the nanorod layer. The enhanced total transmission and reduced total reflection indicate that scattering and absorption are weak in these layers. The antireflection behavior over a broad wavelength range, and the low amount of light scattered, renders these nanorod antireflection coatings a very promising material for enhancing light coupling into solar cells.

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