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Antireflective nanostructures for high-efficiency optical devices

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Ordered and disordered nanostructures with broadband antireflection properties can be used in solar cells, LEDs, and transparent glasses.

Light reflection occurs at the interface between two materials with different refractive indices. In semiconductor materials used in various opto-electronic devices such as silicon and gallium arsenide (GaAs), very high reflectance results from their high refractive indices ($n > 3.0$), which seriously degrade device performance. Single- or multi-layer coatings are commonly used to suppress undesired reflections, but such thin-film technology has inherent problems such as adhesion, thermal mismatch, and stability of the stack.

Recently, antireflective nanostructures (ARNSs) based on the conformation of a moth's eye have become promising for use in high-efficiency optical devices because of their broadband and omnidirectional antireflection properties. ARNSs have a surface layer with a refractive index that varies gradually from unity (air) to that of a bulk material. Therefore, Fresnel reflections are significantly reduced by ARNSs with tapered features. In particular, tapering the shape of ARNSs determines the effective refractive-index profile. Theoretically, a parabola shape has a linear effective refractive-index profile, so it is the optimal shape for reducing surface reflection.

Many fabrication methods have been proposed to obtain ARNSs with tapered functions, including electron-beam/interference or nanoimprint lithography, nanosphere or colloid formation, and Langmuir-Blodgett assembly. However, it is difficult to guarantee the formation of a parabola shape using these techniques, because the ARNS shape depends on a complicated process.

We recently demonstrated parabola-shaped ARNSs fabricated by simple process steps based on a combination of laser-interference lithography, thermal reflow, and subsequent pattern transfer.[1] Use of an additional thermal-reflow process makes lens-shaped photoresist patterns, which enable pattern transfer to realize the parabola shape. Figure 1(a) shows a scanning-electron-microscope (SEM) image of parabola-shaped ARNSs on a GaAs substrate fabricated by the lens-like, shape-transfer method. The fabricated ARNSs consist of parabolic grating patterns, thus resulting in a linearly graded index profile. The morphology of the etched surface is extremely smooth and the

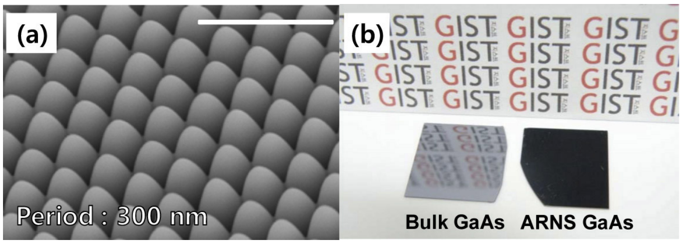

Figure 1. (a) Scanning-electron-microscope (SEM) image of parabola-shaped antireflective nanostructures (ARNSs) fabricated by lens-like shape transfer. Scale bar: 1μm. (b) Photograph of gallium arsenide (GaAs) substrates without and with ARNSs.

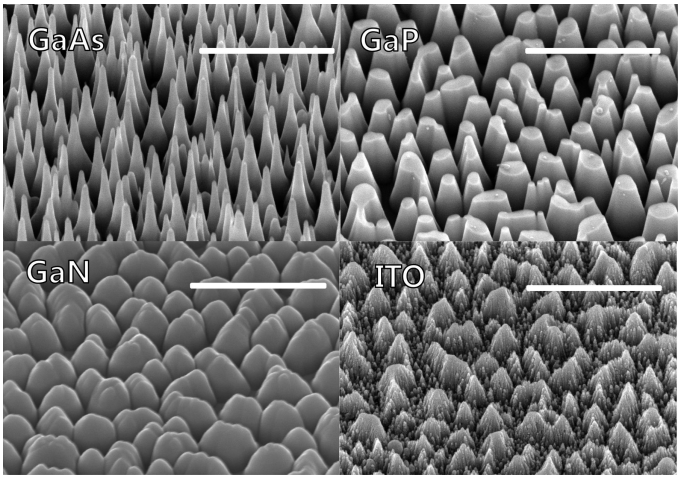

Figure 2. SEM images of ARNSs on GaAs, gallium phosphide (GaP), gallium nitride (GaN), and indium tin oxide (ITO) substrates fabricated by dry etching of thermally dewetted silver nanoparticles. Scale bars: 1μm.

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grating patterns are very uniform. The fabricated sample shows antireflection properties over a broader wavelength range than that of a flat surface or even conventional cone-shaped ARNSs. Figure 1(b) shows that the ARNS sample has a very dark surface because of the lack of light reflection, while the sample with a flat surface has a highly reflective (mirror-like) surface. By implementing these structures on thin-film crystalline-silicon solar cells, the cell efficiency can be improved by ∼25% compared to double-layer antireflection coatings.[2] In addition, nearly 100% transmittance can be achieved by integrating ARNSs on glass or polymer materials.[3,4]

Our second approach for ARNSs is an overall dry-etching process using thermally dewetted silver (Ag) nanoparticles. In this method, the thermal dewetting process of thin-metal films deposited by electron-beam evaporation provides nanoscale etch-mask patterns without lithography, enabling cost-effective fabrication. Moreover, the average nanoparticle size and separation can be controlled by film thickness at a given annealing temperature. Because the fabrication process is not limited to certain materials, the ARNSs can be fabricated on various substrates (see Figure 2). The shape and height of the fabricated ARNSs are very different because they are determined by dry-etching conditions such as process pressure, gas mixture, and radio-frequency power. Even though the structures fabricated by this method are disordered and the shapes are far from ideal, they show broadband antireflection properties that are similar to those of ordered structures.

For optical-device applications, we first implemented ARNSs on the top surface of aluminum gallium indium phosphide (AlGaInP) red LEDs and achieved a 26.4% improvement in the light-output power compared to that of conventional LEDs with flat surfaces.[5] The increased output is attributed to the strong reduction of Fresnel reflection by the ARNSs. The main advantage of Ag nanoparticles is that it is possible to form ARNSs on a patterned or roughened surface, which makes them easy to apply on devices. However, it is difficult to form nanopatterns on a complete device using conventional lithography methods, because these methods are based on a spin-coating process. Using similar techniques, we fabricated gallium nitride-based blue LEDs with ARNSs that showed a 30.2% enhancement of the light-output power.[6]

In summary, we have demonstrated ARNSs fabricated by either lens-like shape transfer or Ag-layer dewetting, which enable ordered or disordered structures, respectively. The fabricated ARNSs with ordered/disordered structures showed broadband antireflection properties compared to flat surfaces. ARNS-integrated LEDs exhibited improved light-extraction performance because of the strong reduction of Fresnel reflection. We are concentrating the next phase of our research on several potential optical-device applications such as ARNS-integrated, thin-film solar cells, highly transparent glasses, flexible films with ARNSs, and broadband absorptive photodetectors.

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Young Min Song is a PhD student. He focuses on antireflective subwavelength structures for optical-device applications including photovoltaic devices, red-green-blue LEDs, and highly transparent optical films. He is also interested in bio-inspired artificial nanophotonic structures. He has authored or co-authored more than 20 research papers in international journals.

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