Nano- and Micro- Lens-array Patterns Formed by Conformal Atomic Layer Deposition

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Lens arrays are the key optical components which are widely used in variety of applications. Despite micro-lens arrays could be made into polymer by various replication methods such as injection molding, surface compression molding, hot embossing, soft lithography and thermal or UV nanoimprinting, a primitive mold is still needed to be made by other fabrication methods. Primitive micro-lens arrays may originate from several existing fabrication methods including photoresist reflow, mass transportation, photolithography (e.g., multi-level or grayscale photolithography), direct laser writing, and ion-beam milling. However, none of the existing methods is capable to make lens arrays with optimal parameters, e.g., size, fill factor, lens material, surface shape/curvature, and surface roughness. For instance, it is difficult with direct laser writing to make high quality microlens array with size (i.e., pitch and diameter) smaller than 5 to 10 microns. For photoresist reflow and photolithography, strong limitations exist on choosing the micro-lens material. Beyond polymer and silicon dioxide, most high index metal oxides are hard to etch. For all the existing methods, lens shape and surface curvature controls are difficult, especially for sub-10 micron sized lenses. Furthermore, it is difficult to achieve microlens array with 100% filling factor which is important for overall light efficiency. For the thermal reflow method, the process conditions must be delicately controlled to create a high fill-factor microlens array, which increases the process difficulties and reproducibility requirements. Last but not least, it is very challenge to fabricate lens with very small surface roughness. All the above limitations on lens size, material, fill-factor, shape and surface roughness greatly affect achieving best quality microlenses with optimized focusing efficiency and optical performance such as scattering loss, numerical aperture (N.A.) and *f* number.

A new micro- and nano- lens array forming method based on conformal atomic layer deposition (ALD) is reported. Both two-dimensional (2D) lens array (Fig. 1 and Fig. 2(a)) and cylindrical lens array (one-dimensional lens array) (Fig. 2(b)) were realized by the new fabrication method. Lens arrays with 100% filling factor and pitch sizes from 200 nm (cylindrical lens), 2 microns (2D lens array) to 20 microns have been fabricated. In addition, different optical materials from low-index (e.g., SiO_2) to medium index (e.g., Al_2O_3) to high index (e.g., TiO_2), and further to nano-laminate material and alternative thin film stacks were used to make the lenses for focusing. This new method is versatile to making wide range of lens arrays in term of size, fill factor, material option, shape and surface curvature, and optical function (e.g., graded-index lens array).

Furthermore, we successfully demonstrated a micro-lens array (Fig. 3) with a multi-layer ultraviolet/infra-red filtering film stack simultaneously functioned as the lens material for focusing.

(a) (b)

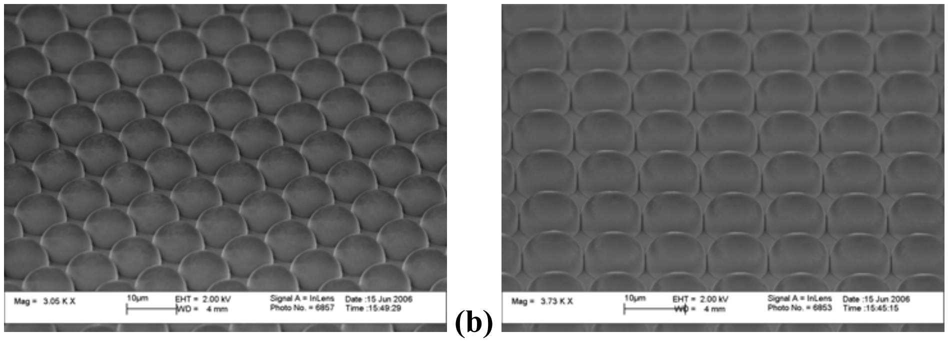

Fig. 1(a) and Fig. 1(b) show micro-lens array with a diameter and a pitch size of 10 μm after 3 μm of ALD growth of SiO_2 onto a template.

(a) (b)

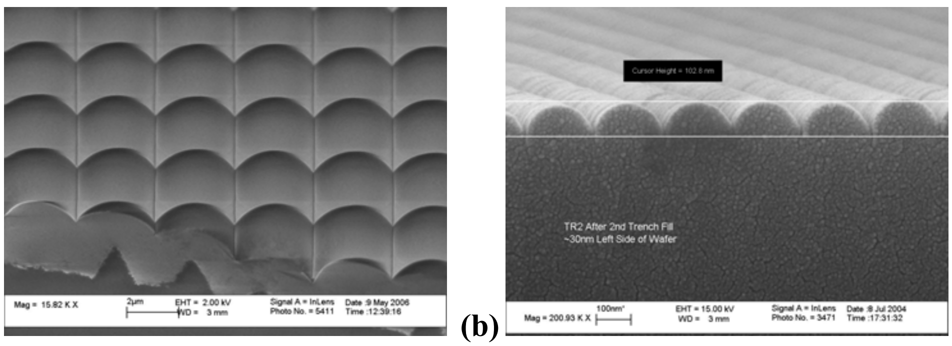

Fig. 2 (a) shows micro lens arrays with lens diameter and pitch of 3 μm with a 100% fill factor. The grown material is Al_2O_3. In Fig. 2 (b), a one-dimensional semi-spherical array (i.e., cylindrical lens array) with a pitch of 200 nm is shown.

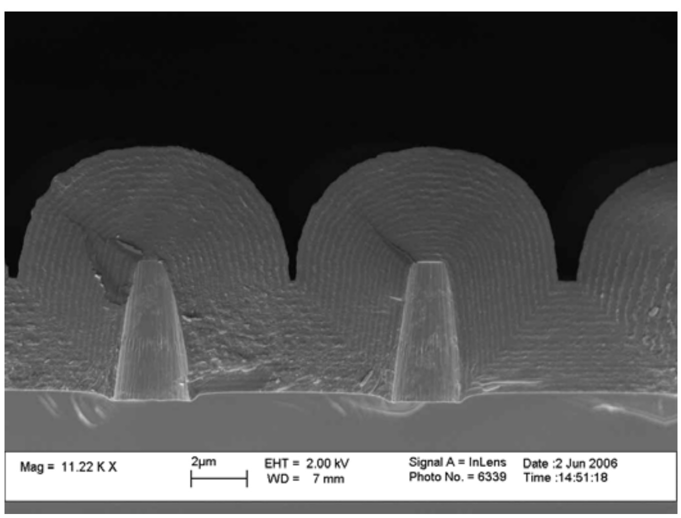

Fig. 3 A film stack initially designed for IR band-pass filter was used to form the lens by the ALD, as shown.