Heterostructure multilevel binary optics

E. Hasman, N. Davidson, and A. A. Friesem

Department of Electronics, Weizmann Institute of Science, Rehovot 76100, Israel

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A method for forming multilevel diffractive elements (kinoforms) that have highly accurate level heights so as to obtain high diffraction efficiencies is presented. The method, which leads to heterostructure multilevel binary optical elements, relies on conventional deposition technology, selective etching, and multimask lithography. As an illustration, a reflective multilevel element for 10.6-μm radiation is designed, recorded, and tested.

High diffraction efficiencies for holographic optical elements can be obtained with kinoforms that are constructed as surface relief gratings on some substrate. Indeed, the diffraction efficiencies of kinoforms that have properly graded surface relief gratings can reach 100%.[1,2] However, in order to reach such efficiencies, it is necessary to resort to complex fabrication processes that can provide the needed accuracies for controlling the graded shape and depth of the surface grooves. Specifically, in one process a single photomask with variable optical density is exploited for controlling the etching rate of the substrate to form the desired graded relief gratings.[3] In another process, the single photomask with the variable density is replaced by a multiplicity of simpler binary photomasks,[4-6] so the graded shape is approximated by multilevel binary steps. Both fabrication processes rely mainly on etching techniques that are difficult to control accurately. As a result, the shape and depth of the grooves can differ from those desired, which leads to reduction of diffraction efficiency and poor repeatability of performance.

In this Letter we present a fabrication process for multilevel elements that depends primarily on deposition techniques that can be accurately controlled to obtain the desired groove shapes and depths with high repeatability. This leads to heterostructure multilevel binary optics (HMBO) that have relatively high diffraction efficiencies. The process is illustrated with a focusing lens operating at a wavelength of 10.6 μm.

In a multilevel binary element each continuously graded groove of the surface relief gratings is approximated with multilevel discrete binary steps.[6] The diffraction efficiency η of such an element is related to the number of discrete levels N by[5]

$$\eta(N) = \left[\frac{N}{\pi}\sin\left(\frac{\pi}{N}\right)\right]^2. \tag{1}$$

The surface of the element must be etched m times in order to obtain a number of levels $N = 2^m$. The proper etch depth Δ_m for each etching should be

$$\Delta_m = \frac{\lambda}{\Delta n 2^m}, \tag{2}$$

where λ is the readout wavelength and Δn is the relief-modulating refractive-index change for transmissive elements, with $\Delta n = 2$ for reflective elements. As the number of levels increases the efficiency becomes higher, reaching 98.7% at 16 levels.

In general, it is difficult to control the proper etch depth accurately, according to Eq. (2), because the rate of the etching depends on many parameters, such as temperature, etch concentration, and oxidation effects. In order to overcome this difficulty, we developed a process for forming HMBO, in which the depth of each level is controlled by deposition of layers rather than by etching. With deposition it is possible to achieve extremely accurate depths; for example, it has recently been shown that accuracies up to one atomic layer may be obtained.[7]

Our process for forming HMBO is described with the aid of Fig. 1. Two materials, denoted A and B, are deposited alternately to form the multilevel heterostructure. Each pair of layers (A + B) forms a single level, of thickness Δ, which is determined according to

$$\Delta = \frac{\lambda}{N\Delta n}. \tag{3}$$

By exploiting multimask lithography and selective etching techniques, in which one of the layers' material acts as a stop, it is possible to obtain a multiplicity of levels, each having a depth that can be controlled with high accuracy.

In order to illustrate the effectiveness of our process, we recorded a reflective HMBO focusing lens for 10.6-μm radiation that had a spherical grating function, a 15-mm diameter, and a 150-mm focal length. Only four levels ($N = 4$) were formed, so two masks were needed. Each of the masks was first plotted as a binary computer-generated hologram, by using a laser scanner (Scitex Raystar Respone 300) having a resolution capability of approximately 10 μm, and recorded directly onto a photographic film. The plots were demagnified optically and recorded as chrome master masks.

Aluminum and Ni–Cr (80:20) were chosen as the alternate materials, denoted B and A in Fig. 1. The aluminum was etched with H_2PO_4–HNO_3–CH_3COOH–H_2O (16:1:1:2) at an etch rate of 2.8 nm/s, whereas the Ni–Cr was etched with

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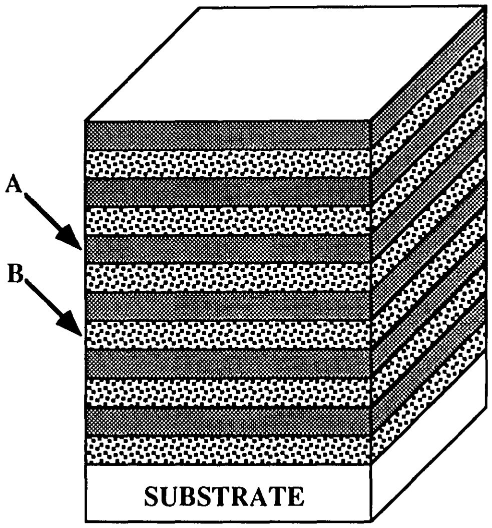
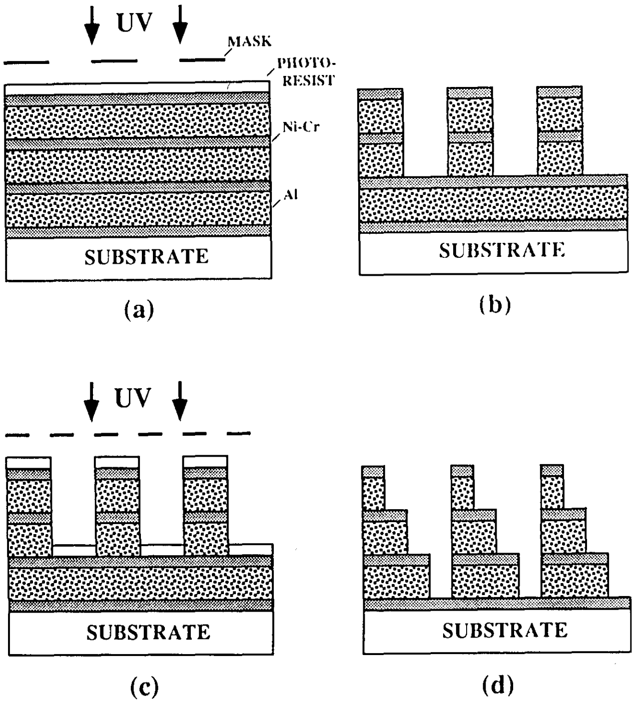


Fig. 1. Multilevel heterostructure configuration.



(a) (b)

(c) (d)

Fig. 2. The HMBO fabrication process: (a) the first UV exposure, (b) the first etching step, (c) the second UV exposure, (d) the second etching step.

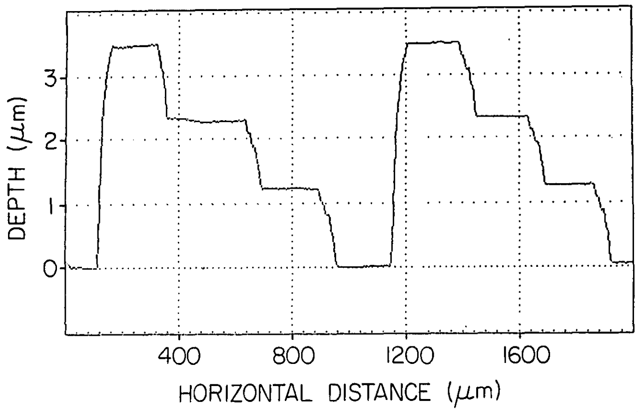


Fig. 3. Surface profilometer trace for a typical etched section.

$Ce(NH_4)_2(NO_3)_6$–CH_3COOH–H_2O (5:1:40) at an etch rate of 2.2 nm/s; both etchants were at a temperature of 40°C. We found that Ni–Cr acts as a stop layer for the aluminum etchant, while the aluminum serves as a stop layer for the Ni-Cr etchant. We deposited four levels ($N = 4$), each of thickness 1.325 μm, as determined from Eq. (3). Each level was composed of an aluminum layer of thickness 0.925 μm and a Ni–Cr layer of thickness 0.4 μm.

The formation procedure of the HMBO lens is illustrated in Fig. 2. The heterostructure multilevel sample was first coated with a 1-μm photoresist layer (Shipley Microposit S1400-27) that was exposed to UV radiation through the first mask [Fig. 2(a)]. After developing the photoresist, the two top levels (four layers) were etched in sequence with the appropriate etchants, and then the remaining photoresist was removed [Fig. 2(b)]. The coating and exposure steps were then repeated with the second mask, after aligning the mask with an aligner having a resolution of approximately 1 μm [Fig. 2(c)]. The final step shown in Fig. 2(d) involves the etching of additional levels. Finally, in order to obtain high reflectivity, a gold layer, with a thickness of 0.1 μm, was vacuum deposited onto the HMBO lens. Figure 3 shows a surface profilometer trace for a typical section of the final reflective lens.

Several identical HMBO lenses were recorded, and their diffraction efficiencies and resolution capabilities were measured. The illumination source was a CO_2 laser operating at 10.6 μm. We found that the performance of all lenses was highly repeatable. The diffraction efficiencies (the ratio of diffracted power into the first order to the incidence power) was close to the theoretical value of 81.1%, as given by Eq. (1) for four levels. The resolution capabilities were determined by measuring the focused spot size with the scanning-knife method.[8] The results revealed that the spot size for all lenses was approximately 260 μm, which is also the predicted value for our lenses with focal number of 10.

To conclude, we have shown how the heterostructure technology can be combined with multilevel binary optics to form elements that have highly accurate level heights and easily repeatable performance. We have demonstrated such a combination to form four-level HMBO focusing lenses whose performance matches the theoretical values. By increasing the number of levels it would of course be possible to reach diffraction efficiencies close to 100%.

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