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Non-conventional techniques for optical lithography

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1. INTRODUCTION

The best known conventional techniques for microlithography are contact printing, proximity printing, and wafer steppers. Contact printing is simple and offers high resolution, however, the contact can damage both the photomask and the substrate, and so it is not suitable for large production quantities. Proximity printing avoids the direct contact between photomask and substrate, but for the price of reduced resolution because of light diffraction. The wafer stepper operates by imaging the photomask onto the substrate using a complex lens system to get high resolution. Although this avoids the problem of contact, the camera can only image a small pattern of a few cm^2 and so has to "step" across the substrate to print a large area.

However, there are applications of microlithography where non-conventional techniques are more adequate. This is the case when high resolution and high dimensional accuracy over large fields is required; examples are surface-acoustic wave (SAW) devices, integrated and diffractive optics, infrared imaging systems and CCDs. Another class of applications are flat panel displays, such as active-matrix liquid crystal and field-emitter displays, which require very large areas of relatively simple repetitive structures.

Recent work [1-4] has demonstrated the potential of total internal reflection (TIR) holography [5] for microlithography. Holographic lithography is now beginning to achieve industrial acceptance as a valid alternative to conventional techniques. In 1993, Holtronic Technologies made a bold entry into the market with the world's first holographic mask aligner system [6]. Two systems are presently installed in fabs in Europe, with encouraging results stimulating further interest in the Far East and U.S.

More recently, the use of lenslet arrays for large field lithography of moderate resolution (> 2 μm) has been proposed [7]. Thanks to micro-lithographic techniques, large arrays of refractive or diffractive micro-lenses become now feasible. For periodic structures (flat panel displays) self-imaging, known as the Talbot effect, could be used favorably.

2. HOLOGRAPHIC LITHOGRAPHY

In this chapter we will look at the attributes of holographic imaging and why it differs fundamentally from conventional techniques. The physical principles will be outlined, although for the sake of brevity we will not go into the details, which are in any case available elsewhere [2,3]. Instead, we will concentrate, with reference to actual results, on system performance. We will also look at the future potential of holographic lithography.

2.1. Basic concept of TIR holography

Holography is the recording of a wavefront emanating from one or more objects. This wavefront (the object beam) is stored in the form of an interference pattern between itself and a reference wavefront (usually a plane wave). Replay of the hologram then recreates, under the correct conditions, the original wavefront. In the case of holographic lithography, the "object" is a photomask, and replaying the hologram recreates an exact image of the photomask pattern. A resist-coated wafer placed in the plane of the original photomask will thus be perfectly printed.

Early experiments with holography [8] were frustrated by the recording configuration and lack of stable recording material: it was difficult to get the photomask close enough to the recording emulsion to achieve a high numerical aperture (NA) because of the necessity to leave room for the reference beam. A reference beam incident from behind the recording emulsion on the other hand will usually interact with the photomask and produce spurious images. Furthermore, replay of the hologram in these cases would lead to the resist being partially exposed by the replay beam.

Stetson [5] however devised an ingenious configuration which circumvented these problems. His geometry, shown schematically in Fig. 1 is known as TIR holography because of the total internal reflection of the reference beam, and is the method used exclusively by Holtronics.

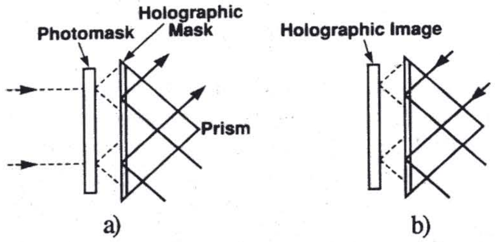


Figure 1. Schematic diagrams of (a) TIR holographic recording geometry and (b) replay geometry.

The holographic plate comprises a film of HRS-352, a high-resolution photopolymer [9] manufactured by Du Pont de Nemours & Co., spun onto a glass substrate. The material records the hologram as a complex, high spatial frequency variation of the refractive index. Unlike the previous generation of holographic recording materials, such as silver halide emulsions or dichromated gelatin, the dimensions of the HRS-352 material remain very stable throughout the exposure process and thereafter.

The properties of the TIR hologram geometry need to be appreciated. The most striking feature is the absence of imaging optics: unlike the projection stepper whose image field and resolution are limited by off-axis aberrations, the TIR hologram has no optical axis and so off-axis aberrations are zero. The implications are enormous: a hologram of a photomask can be replayed in its entirety, with diffraction limited resolution, and without recourse to stepping. The geometry is non-contact and as simple as proximity printing without of course the loss of resolution caused by proximity diffraction.

A further useful feature of holograms is their built-in redundancy. Due to diffraction each mask feature is recorded over an area much larger than the feature itself, which gives a certain tolerance to small particle contamination.

TIR holographic lithography thus offers a unique combination of non-contact, full-field, diffraction limited printing. We will now look at how this powerful optical element is incorporated into a production mask aligner.

2.2. The HMA 150 Holographic Mask Aligner

The HMA 150, shown in Fig. 2, is a fully automatic precision holographic mask aligner for wafers and substrates of up to 6 " diameter.

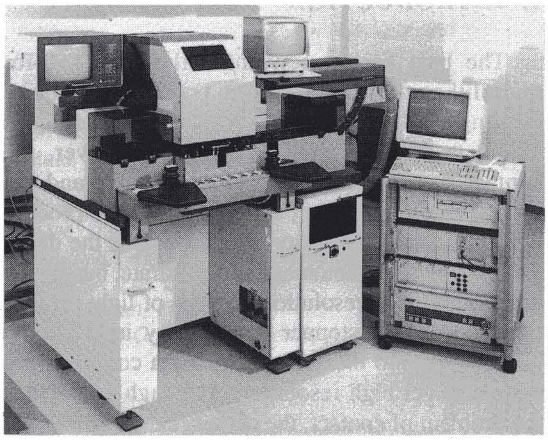


Figure 2. Holtronics HMA 150 production holographic mask aligner.

Resolution is easily achieved at 0.5 µm over the full field, although with careful processing some users have in practice achieved 0.3 µm or even 0.25 µm resolution (see 2.3). Wafers are exposed by scanning a small u.v. beam over the hologram in an overlapping x-y raster scan. The reasons for scanning are two-fold; firstly, the exposing laser beam has a Gaussian intensity profile so scanning is necessary to produce a uniform illumination field. The second reason is to overcome wafer non-flatness. Referring to Fig. 1, it will be seen that the wafer will only be in focus when it is in the plane of the original photomask. As wafers are never perfectly flat, a system is needed to follow the wafer terrain. Such a system is included in the HMA 150 system: an autofocus interferometer beam scans synchronously with the exposing beam, continuously detecting out-of-focus conditions and correcting them in real time. A PZT transducer in the wafer chuck ensures rapid response. (In fact the autofocus interferometer can even be used independently for measuring wafer flatness before printing. Data is mapped out to give a topographic map of the wafer).

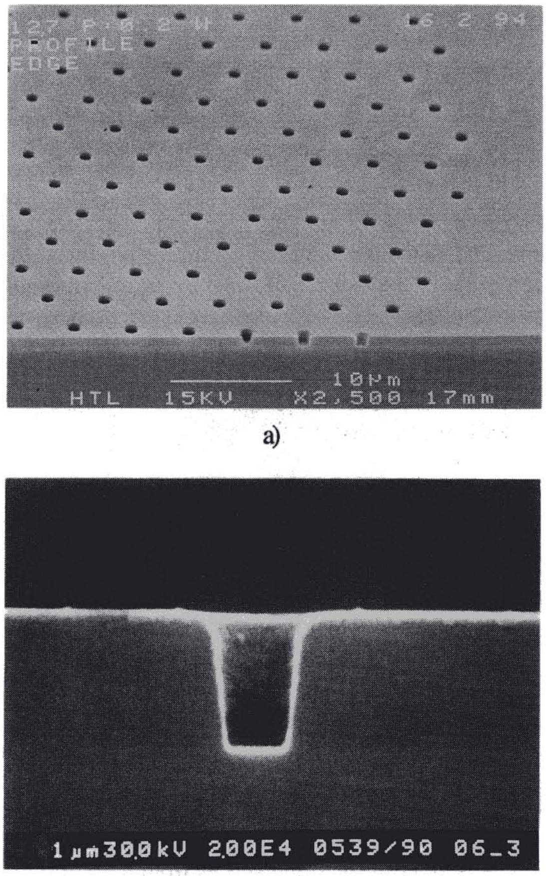
The appearance of the HMA 150 may be familiar to some readers: indeed the base of the machine is adapted from a Karl Süss MA 150 mask aligner. This base comprises the cassette-to-cassette wafer transport, wafer pre-alignment, wedge compensation and pre-focus functions as well as the precision x-y-θ movements for layer-to-layer registration. Alignment between levels is carried out by simultaneously imaging conventional chevron marks on the wafer with corresponding marks in the hologram. The image is captured and digitized, and offsets quickly calculated to apply corrections in x-y and θ. In this way layer-to-layer registration of ± 0.3 µm is routinely achieved. The overlay measurements obtained can also be used for correction of wafer scale changes during processing.

The illumination source is an argon-ion laser operating at a wavelength of 364 nm, compatible with i-line photoresists. Depending on the space available and the throughput required, a small- or large-frame laser may be used. Previously engineers have been hesitant about using lasers in a production environment. Modern ion lasers however offer turn-key laser light, with complete hands-off operation [10]. Built-in sensors keep the laser beam aligned and laser power uniform. Collimating optics shape the beam to the required dimension and the beam is fully enclosed.

2.3. Results and Applications

Applications are diverse and vary between users for whom holography is an enabling technology, such as flat panel displays and SAW devices, and small producers and research labs who need stepper performance but do not have a stepper budget. (A holographic aligner, by virtue of its simple optical system retails for less than a third of the price of a comparable stepper).

Flat panel displays are poised to become a major user of holographic lithography. Manufacturers are pushing for high-resolution displays, but steppers are fundamentally unsuited to the task of large area lithography: in many cases the patchwork of stepped and repeated fields is clearly visible. Fig 3a is a SEM of structures printed holographically for a flat screen application. Resolution is of the order of 1 µm, a resolution obtained over the whole 6" diameter field, without of course recourse to stepping. Fig 3b is a detail of a similar display, with even tighter resolution: 0.6 µm.



a)

b)

Figure 3. (a) Part of a holographically printed wafer for a flat panel display application.
(b) A detail of a similar display showing 0.6 µm resolution.

Figures 4 and 5 are examples of higher resolution structures (0.3 µm). A characteristic of all of these results is the vertical sidewalls; in the case of Fig. 4, the sidewalls are even slightly under-cut by virtue of the image reversal process employed.

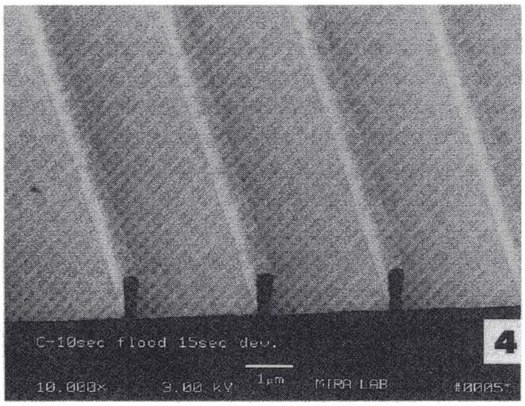


Figure 4. SEM of part of a grating structure for infra-red detection systems; structure produced by holographic exposure followed by image reversal process (courtesy Loral Vought Systems, Inc.).

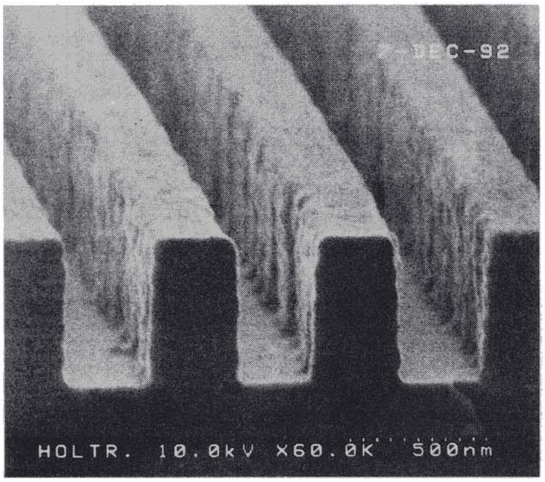
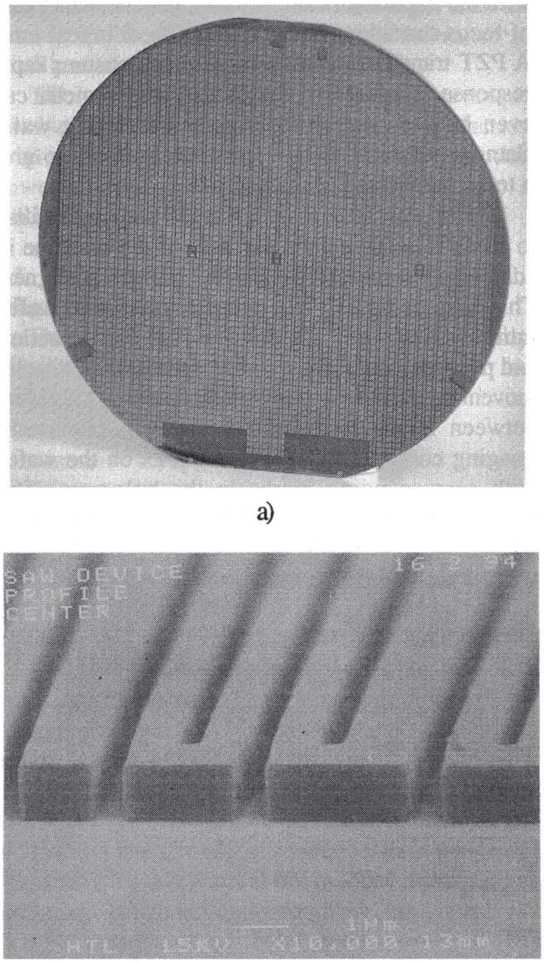


Figure 5. 0.3 µm lines and spaces from a grating for solar cell coating application (Photo courtesy PSI, Zürich).

Figure 6a is a photo of a 4" silicon wafer printed with a single holographic exposure, indicating the high uniformity achieved, while Fig. 6b is a detail from the wafer showing (again) 90° sidewalls and good contrast. This print is for high frequency SAW devices, an application requiring exceptional critical dimension and placement accuracy which is intolerant of the lens aberrations typical of stepper exposures.



a)

b)

Figure 6. (a) Photo of a 4" wafer printed in a single exposure using an HMA 150. (b) Detail from the same wafer showing microscopic SAW device structure.

Figure 7 shows 1.0 µm lines of resist printed over a polysilicon step of 2.0 µm with negligible line deformation which demonstrates the validity of holographic printing even onto difficult topographies.

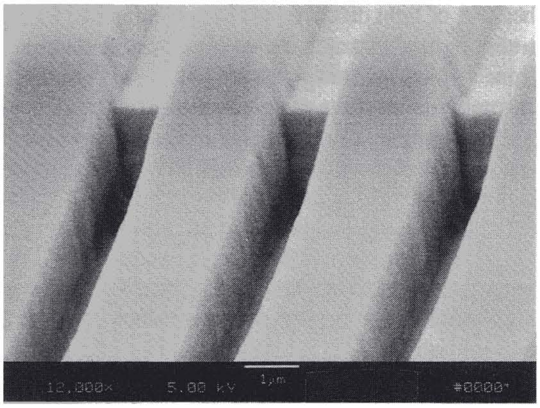


Figure 7. 1 μm lines crossing a 2 μm poly Si step with no deformation. (Photo courtesy Loral Vought Systems Inc.).

Another application requiring large area lithography is integrated optics. Here again, TIR holography has achieved impressive results. Figure 8 shows a detail from a 70 mm long waveguide device.

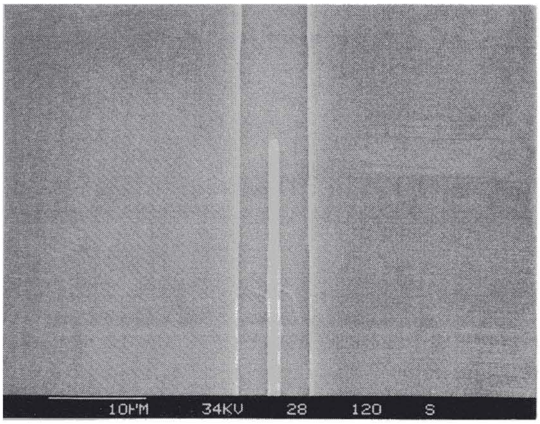


Figure 8. Detail from a holographically printed optical waveguide circuit.

For most demonstrations we have obtained good results with O.C.G 6500 resist, a cross-over g-line/i-line resist. A typical process is: spin-coat; soft-bake at 90°C in oven 30 min; expose; post exposure bake 120°C on hot plate for 60", develop in 460 developer by immersion for 60". Most of the results shown use this process, although for higher resolution work we believe that a higher performance resist will yield even better results.

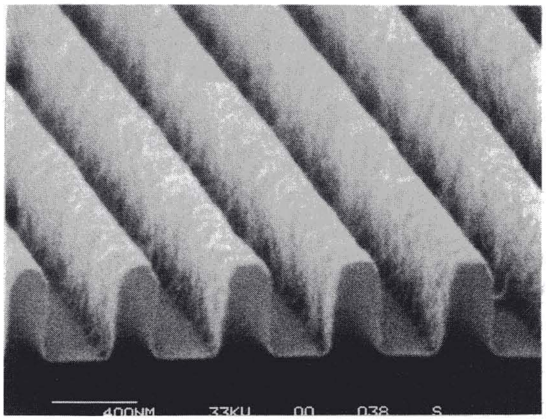


Figure 9. 0.25 μm lines and spaces holographically printed into 0.5 μm O.C.G 6505 resist. (Photomask produced by Litomask at CSEM).

2.4 Outlook

We have claimed the characteristics of holographic lithography to be "diffraction-limited resolution" and "unlimited field size". This is true in principle, but what about the practical limitations.

A hologram is an imaging system, its resolution w is therefore limited by the Rayleigh criterion

$$w = K_1 \lambda / NA , \qquad (1)$$

where K_1 is a process factor, λ is the wavelength of the light and NA is the numerical aperture of the imaging system. The difficulty in defining the absolute resolution limit comes from the ambiguity of the quantity NA for a TIR hologram. Unlike a lens system, a TIR hologram has no defined aperture. All of the light passing through the photomask reaches the recording layer and so we may therefore expect a NA of 1. In practice however, Fresnel reflection, polarization effects and the response of the recording material itself limit the NA to less than this.

The resolution limit of a TIR hologram can be experimentally determined. The highest resolution so far achieved using the standard holographic system is 0.25μm (see Fig. 9), but at these dimensions high quality masks become increasingly difficult to obtain (although Litomask of CSEM have supplied some good masks to our customers). With the current increase in activity and interest in 1× mask manufacture being pushed by X-ray lithography, Ultratech

/HP, and now holography, and with careful processing of high performance i-line resists, the resolution limit may well extend below the quarter micron.

With respect to field size, the limit is set by the photomask itself. For flat panel displays, substrates up to 500 mm x 500 mm are necessary. Holtronic is in fact currently engaged in an Esprit Project to develop the technologies for making 12" diagonal displays on 300 mm x 400 mm substrates. Working with display manufacturers, mask makers and end-users, Holtronic is constructing a large substrate printer for commissioning in early 1995.

Flat panel displays are an application area where holography's combination of high-resolution and full field printing is unique. For high resolution direct view displays like Field Emitter Displays, or for even more demanding projection display valves such as AMLCD or the Digital Micromirror Device (DMD), holographic lithography could really prove an enabling technology.

For certain applications, and especially IC manufacture, overlay of better than 0.1 µm is often necessary. Holtronic is currently developing such a system [6] which uses overlapping diffraction gratings to achieve a measurement accuracy of ±50 nm. This will, when incorporated into a second-generation system, open up further application areas.

3. MICRO-IMAGING LITHOGRAPHY

A special class of applications are flat panel displays, such as active-matrix liquid crystal, which require very large areas of relatively simple repetitive structures. This type of devices will see a strongly increasing market and the fabrication methods are still under development. It is therefore worthwhile to look for lithographic techniques, which respond to the special requirements of large field printing of moderate resolution and high throughput for mass-production. Self-imaging and micro-imaging could be solutions.

3.1. Self-imaging

Contact printing is simple and offers high resolution, however, the contact can damage both the photomask and the substrate, and so it is not suitable for large production quantities. Proximity printing avoids the direct contact between photomask and substrate, but for the price of reduced resolution because of light diffraction. The self-imaging properties of periodic structures under coherent illumination, known as Talbot effect [11], could be used favorably to improve the printing quality.

Self-imaging of periodic structures is observed at specific distances z, which are given by

$$z = 2n\Lambda^2/\lambda , \qquad n = \text{integer}, \qquad (2)$$

where Λ is the periodicity and λ the illumination wavelength. Figure 10 shows the Talbot image of a periodic object with Λ = 300 µm. The illumination wavelength was λ = 488 nm from an Ar^+ laser. The first Talbot self-image is then observed at a distance of 369 mm from the mask.

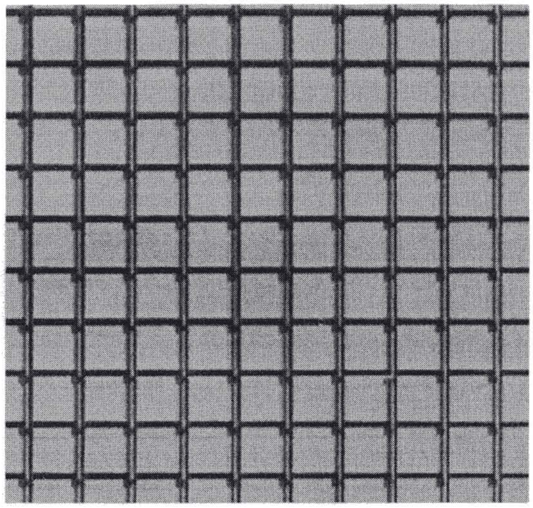


Figure 10. Lens-less image of a 300 µm periodic structure at the Talbot distance z = 369 mm.

3.2. Micro-lens array lithography

Geometrical aberrations shrink proportionally with the lens size. Therefore, imaging of large areas can be performed favorably by arrays of micro-lenses, where each lens images only a small field, as shown in Fig. 11a. Image inversion can be avoided by using a three-lens array system sketched in Fig. 11b. Many micro-devices have a repetitive and discrete nature with respect to some unit element which lends itself well to the imaging properties particular to lens arrays. Each lens of the array can be made to correspond to the unit cell of the particular micro-device.

With this technique it is possible to make a single exposure over a comparatively large area, thereby eliminating step-and-repeat operations and thus reducing the exposure time. A ray-tracing analysis shows that already a simple spherical microlens of 1 mm focal length and 300 µm aperture produces a nearly diffraction limited resolution in the order of 3 - 5 µm over a field of 300 µm x 300 µm. Improved characteristics can be expected by using more complex systems, including refractive as well as diffractive (binary) optics.

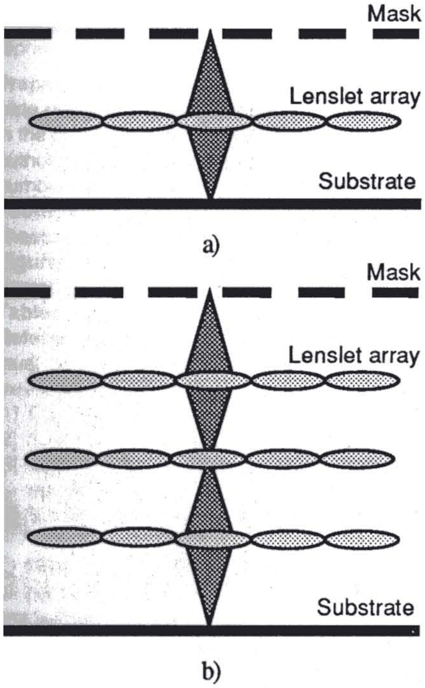


Figure 11. Photolithography using lenslet arrays. a) Single lens producing an inverted image. b) Three-lens system for non-inverted imaging.

Figure 12 shows as an example a periodic structure with $\Lambda = 300$ µm imaged through commercially available Corning lenslets of 200 µm diameter and 200 µm focal length. The finest lines in the structure are 16 µm wide.

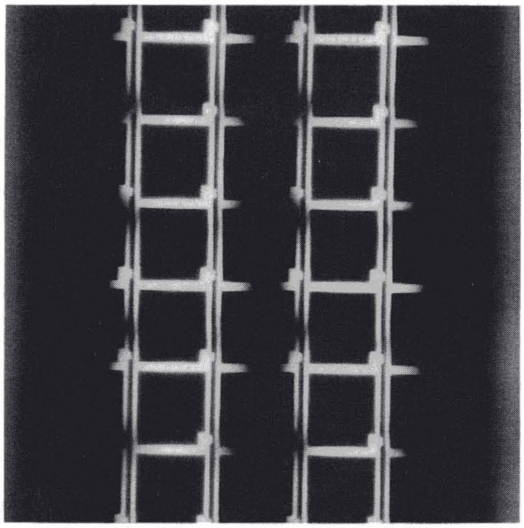


Figure 12. Periodic structures imaged through commercially available lenslets (Corning).

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