Nanolithography using high transmission nanoapertures

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Nanoscale ridge apertures concentrate and transmit light with high efficiency for use in nanolithography.

Both the microelectronics industry and the research community have a keen interest in next-generation nanolithographic techniques. Conventional nanolithography produces sub-100nm structures using electron beam and other short-wavelength radiation sources. But the systems required to generate and manipulate these beams are sophisticated and expensive. Moreover, beams can only be used one at a time, and this serial processing adds to the overall cost of manufacturing.

Low-cost, off-the-shelf commercial laser systems provide attractive alternative light sources at visible or ultraviolet optical wavelengths for nanolithography. The challenge in using them is to overcome problems of resolution posed by the diffraction limit. Methods such as those based on near-field scanning microscopy (NSOM) aim at reaching subdiffraction-limit resolution. However, the light throughput of an NSOM system is low, and this method, too, is a serial process. We are developing a parallel optical nanolithography method that has the potential to speed up the nanomanufacturing process.

The key to our approach is a nanoscale optical antenna aperture capable of concentrating light in nano dimensions with high transmissivity. The idea is to use the concentrated radiation from the aperture for lithography. A number of optical antenna designs belong to a class of ridged-aperture devices. Figure 1 shows two examples schematically. The example on the left with straight ridges is called an H-shaped aperture and is cut out of a thin metal film (~100nm thick) layered onto a transparent substrate such as quartz. Irradiation from one side of the aperture induces electric potential and, hence, currents in the ridges of the antenna. Because the field is strongest across the gap between the ridges, the field transmitted through the H-shaped aperture is concentrated in the central region, the size of which is determined by the dimension $d$ of the gap. Compared with a regularly shaped nanoaperture (square or circle), the waveguide propagation mode results in much higher optical transmission.

A second optical antenna shown in Figure 1 has a ‘bowtie’ geometry with tapered ridges. Compared with the H-shaped aperture, the bowtie antenna has an additional advantage: the sharpness of the apexes concentrates charges, resulting in a higher displacement current across the gap. This produces a stronger field, similar to a Hertzian dipole. The sharpness of the bowtie tips further enhances local transmission.

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Figure 3. This atomic-force-microscope image shows a 2×2 array of holes produced by a 2×2 bowtie array.

Numerical calculations have confirmed our findings for the ridge apertures, including C,1 H,2 and bowtie shapes.2–4 These numerical calculations show that transmission through the apertures is indeed concentrated in the gap region and has about the same intensity (power per unit area) as incident intensity or higher. The transmission intensity is orders of magnitude higher than that through regularly shaped apertures of the same size. NSOM5–7 and far-field photoluminescence8 experiments also show the field enhancement effects. The NSOM measurements provide direct evidence that the field emerging from the apertures is concentrated in the nanoscale domain.

To demonstrate the plausibility of using these nanoscale ridge apertures for nanolithography, we placed nanoapertures in contact with a photoresist, and shone a laser beam at a wavelength of 355nm through the apertures. We followed up with standard photoresist development procedures. In the experiment, a number of apertures—a bowtie aperture, a larger square aperture of 100×100nm, a smaller square aperture of 30×30nm, and a rectangular aperture of 280×36nm—were irradiated simultaneously for comparison: see Figure 2(a). Results showed that the bowtie aperture produced a 50nm-diameter hole in the photoresist, and the rectangular aperture produced a hole more than 200nm in diameter.9 The square apertures yielded no measurable results. Due to the planar geometry of the ridge apertures, it is possible to fabricate a (large) number of apertures in the same plane for parallel processing. Figure 3 shows a 2×2 array of holes produced by a 2×2 array of bowtie apertures. The sizes of the holes produced vary by less than 10%.

In summary, we have demonstrated the possibility of using nanoscale ridge antenna apertures for nanolithography. Our next step will be to make both a larger array and complex patterns. In addition, we expect that the ability to concentrate light in nano dimensions with high efficiency will have application in other areas of science and technology: from surface inspection and biological detection to high-density optical or hybrid data storage.

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References