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MICROSTRUCTURES FOR USE IN A LASER-POWERED LINEAR ACCELERATOR**

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MATERIAL CONSIDERATIONS IN THE MICROFABRICATION OF GRATING MICROSTRUCTURES FOR USE IN A LASER-POWERED LINEAR ACCELERATOR

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ABSTRACT

Collaborative work between Brookhaven and Los Alamos National Laboratories is developing a new type of linear accelerator that uses a high-power, picosecond pulse CO_2 laser to irradiate a specialized form of grating with a pitch of 10.6 microns. The electromagnetic field that results can be used to accelerate electrons at field gradients of several GeV/m with potential efficiencies much better than current accelerators. The grating must be conductive to minimize resistive losses, be able to withstand high fields without damage, and requires dimensional tolerances in the sub-micron range. These requirements focus attention on grating material selection, microfabrication methods, and metrological methods used for quality control. At present, several types of gratings have been manufactured by reactive ion etching of fused silica in CHF_3/Ar or etching silicon with $\text{KOH}/\text{H}_2\text{O}$ or ethylenediamine-pyrocatechol solutions. Metrological analysis of the gratings has begun with a Tracor Northern 5700 digital image analyzer.

INTRODUCTION

Recent work by Palmer[1] has demonstrated that it is possible to accelerate charged, relativistic particles with an "open" grating structure that consists of an array of micron-scale projections etched on an optically flat surface. In this scheme, a cylindrical lens is used to focus a polarized laser beam such that the focal point lies a few microns above the longitudinal axis of the grating. For an appropriately-shaped grating, the electromagnetic field is formed such that the electric field vector lies along the grating axis and accelerates electrons in the same direction. To reduce the total stored electromagnetic energy, the grating dimensions must be as small as practical while still allowing an accurate grating to be manufactured. If this concept is confirmed by experiments planned for the near future at Brookhaven, it may be possible to build a linear accelerator that will accelerate electrons to several TeV. Such an accelerator would consist of a precisely aligned array of gratings several hundred meters in length. Its performance could be matched only by conventional accelerators of much larger physical size and greater power consumption.

The grating surface must be conducting to minimize resistive field losses and must be sufficiently rugged to withstand repeated irradiation by picosecond-length, infrared pulses produced by the CO_2 laser. Power levels must be kept below the damage threshold, for any localized melting or pitting that alters the grating surface will degrade the electromagnetic field.

Single crystal silicon and fused silica were chosen for the initial gratings. Both of these materials have been extensively studied in connection with the fabrication of integrated circuits. They are resistant to thermal shock, have well known laser damage characteristics, and have been the subject of numerous microfabrication experiments. Their primary disadvantage, low conductivity, can be rectified with standard metallic deposition methods.

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Chemical and reactive ion etching were used to form two different types of grating that were subsequently examined in the scanning electron microscope. The dimensional accuracy of the gratings was measured with a Tracor Northern 5700 analyzer that digitizes the analog SEM signal, and then computes the area, diameter, and inter-unit spacing of any chosen grating structure in the SEM image.

RESULTS AND DISCUSSION

Two candidate grating structures are shown in Fig. 1. The first consists of a double array of columns with a center-to-center spacing equal to one-half the laser wavelength. The second consists of a series of cavities, one wavelength deep, linked by a narrow channel. In both cases, close control of both the height and spacing of the grating subunits is essential. Both of these gratings were manufactured by generating a reticle with an EW Mann 3600 pattern generator, and then using a photorepeater to produce several dozen of the reticle patterns on standard anti-reflective chrome masks. The pattern was then transferred to fused silica or $\langle 110 \rangle$ silicon wafers using Kodak 820 photoresist.

The fused silica wafers were etched in a Plasma Technology etcher in the reactive ion etch mode. By using deposited Cr or Al layers as the mask for fused silica, it was found that columns 5 microns high could be etched in a 50:50 mixture of CHF_3 and Ar using a power level of 1 wt/cm^2 and an electrode distance of 50 mm. The degree of anisotropy of the etch varied considerably according to choice of the substrate material. Glass supports for the wafers formed vertical walled-columns but considerable crosscontamination. Apparently, sputtering from the substrate formed the "grass" growing on the grating floor shown in Fig. 2a. This problem was eliminated by using a silicon wafer as the substrate at the loss of some degree of anisotropy in the column's wall. The conical columns (Fig. 2b) are not the result of an "isotropic" etch as SEM measurements show that the diameter of the column top is unchanged from the original mask.

Chemical etchs such as 44 wt% KOH-water and ethylenediamine-pyrocatechol-water (EPW) solutions were used to form the cavity grating in silicon. Both of these solutions have the capability to etch vertical-walled structures in $\langle 110 \rangle$ silicon with aspect ratios equal or superior to reactively ion etched samples[2]. The primary disadvantage of this technique is the inability to form outside or convex corners since rapidly etching planes will be exposed at the corner and considerable under-cutting will result. For this reason, a columnar structure cannot be formed with either of these solutions. The cavity-shaped grating structure is achievable but only when the cavities are interconnected. In both $\langle 100 \rangle$ and $\langle 110 \rangle$ orientations, $[111]$ planes lie at an angle to the wafer surface. If attempts are made to etch a simple rectangular cavity, these planes are exposed and the resulting cavity has a floor composed of sloping $[111]$ planes. If the cavity is open-ended, however, the intersecting $[111]$ planes are consumed and it is possible to form the cavity similar to the design in Fig. 1b. As shown in Fig. 3, the EPW solution proved superior in producing both a vertical wall as well as a flat bottom to the cavity.

While chemical etching of $\langle 110 \rangle$ silicon can produce vertical walls with aspect ratios superior to reactive ion etching, only this wafer orientation can be used and the range of etchable geometries is quite limited. Reactive ion etching can etch a wide range of materials with no restrictions as to geometry, but in most cases, the height of the structures is limited to a few microns.

A Tracor Northern 5700 image analyzer interfaced to a JEOL35 SEM was used for the metrological analysis of the grating structures. Considerably more information is needed to characterize the gratings than just simple line width measurements required in integrated circuit manufacture. For the columnar grating, the diameter, area, and the intercolumn distance must all be determined.

Analysis proceeds by digitizing the SEM secondary electron signal with an 8-bit analog digital converter. Each pixel of a 512x512 image is assigned one of 256 intensity values. If the signal gain is correctly adjusted, high intensity values can be set to correspond only to the portion of the image produced by the individual columns in the grating. Standard methods of quantitative metallographic analysis can then be used to determine the area, diameter, and position relative to the edge of the image for each column. The accuracy of the measurement is set by the SEM magnification: the fewer the columns in the image, the greater the accuracy of the calculated parameters. In practice, two columns are positioned in the field of view to allow the calculation of the center-to-center distance between columns. It must be emphasized that the accuracy of the calculation depends on many variables such as calibration of the SEM's scan coils that control the magnification, choice of secondary or backscattered signals, charging, and the angular orientation of the grating with respect to the detector. All of these parameters must be maintained at preset values if repeatable results are to be obtained. For the measurements on the gratings, our SEM was calibrated with latex spheres of a diameter of 1.6 microns with a standard deviation of 0.01.

Metrological results obtained with this method are shown in Fig. 4. For these measurements, one of the columnar gratings etched on a fused silica wafer was coated with 20 nanometers of Au-Pd and examined in the SEM at a 0° tilt angle. As shown in Fig. 4a, it was easy to adjust contrast so that the projected area of the individual columns appeared brighter than the floor of the grating. The bright portion of the image was then digitized and the area, diameter, and intercolumn distance was then measured. Forty-eight out of a total of 600 columns in the grating were analyzed.

Standard deviations for the various parameters are shown in Fig. 4b. The standard deviations proved to be 1% or less for the intercolumn spacing, increasing to about 4% for the area determination. It is thought that most of the inaccuracies result from expansion or contraction of the photoresist during development. Since photoresist must be used both to pattern the original mask as well as the grating itself, any such errors are cumulative. A process involving the fewest number of processing steps, such as a direct-write-on-wafer scheme using electron beam lithography is inherently the most accurate.

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Fig. 1. Two possible grating structures are (a) a double row of columns with dimensions of $5\ \mu\text{m}$ center-to-center and $5\ \mu\text{m}$ high and (b) a row of interlocking cavities approximately $5\ \mu\text{m}$ square and $10\ \mu\text{m}$ deep. Each grating will be $3\ \text{mm}$ long and contain 300 subunits.

Fig. 2. Reactively ion etched column gratings in fused silica. Both structures were etched in 50:50 $\text{CHF}_3\text{-Ar}$ but the grating in (a) was placed on a glass substrate while (b) was placed on a silicon wafer.

Fig. 3. Attempts to etch the cavity grating in 44 wt% KOH-H₂O at 60°C (a) and EPW at 90°C (b). Both solutions produce vertical walls but only EPW is successful in forming a flat bottom to the cavity. The faint traces on the floor of the grating are intersections between the (11 $\bar{1}$) planes and the (110) surface.

Fig. 4. The columnar grating of Fig. 2b is oriented at a 0° tilt angle so the top of the column appears face-on to an observer. The area of the bottom of the column can then be measured by digitizing the high intensity region and summing each pixel contained within. The center-to-center distance is found from $[(x-x_0)^2 + (y-y_0)^2]^{1/2}$ where x , y and x_0 , y_0 , are the centroids of each column's projected area. The standard deviation, σ , for each set of measurements is shown in (b).