

A METHOD FOR THE MASS PRODUCTION OF ICF TARGETS\*

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The application of semiconductor process technology to the manufacture of inertial-confinement fusion targets is described. The use of optical and electron-beam lithography together with silicon etching technology allows the reproducible fabrication of a variety of target configurations for research and may provide a means for the high-volume production of low-cost targets for commercial reactor systems.

1. INTRODUCTION

Laser-induced thermonuclear fusion has been produced by the implosion of glass-shell pellets internally pressurized with gaseous deuterium-tritium mixtures [1]. Existing techniques for producing the required fusion targets have generally been directed at the realization of limited quantities of targets for research and have not been readily adaptable to high-volume production. They also have allowed limited variation in the target configurations used for research, although advanced, structured target designs have been discussed theoretically in the literature [2]-[5].

Two important goals for inertial-confinement-fusion pellet technology are the development of pellet fabrication processes capable of (1) realizing low-cost reproducible target structures in the high volumes required for commercial reactor systems, and (2) of realizing a variety of target designs for research applications. In general, a pellet will consist of both a container to hold the thermonuclear fuel and a hyperstructure of shells, layers, and/or coatings around the container, designed to enhance the response of the pellet to irradiation by the laser or other drivers. The required technology base must provide the means for producing both the container and the hyperstructure. Hollow spherical shells made of glasses, polymers, or metals are currently used as containers.

The process technologies developed for silicon integrated circuits are known to be cost effective in high-volume production, allowing complex circuits containing thousands of transistors to be realized with precise dimensional control. Silicon has probably been studied more than any other material, and its associated process technology is highly developed. In addition to its useful electronic properties, silicon also has the advantage of being a material which can be shaped into a number of structures using photolithographic, etching, and sealing processes. This paper examines the application of this silicon-based technology to the production of next-generation pellet structures. One possible pellet configuration resulting from such a process is shown in Fig. 1.

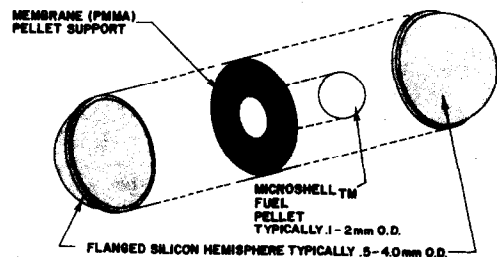


FIG. 1 A NESTED PELLETT STRUCTURE FOR NEXT-GENERATION ICF RESEARCH (EXPLODED VIEW).

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2. PROCEDURES

Precise dimensional control can be achieved using optical or electron-beam lithography [6]. Using optical lithography with visible light,

depth-of-field restrictions force the substrate to be in close proximity to the mask and hence to be typically a planar surface. Minimum feature sizes are about 2  $\mu\text{m}$ . Electron-beam lithography offers great depth of field and can be applied to non-planar substrates, realizing features having submicron dimensions. Mask openings of any desired shape in the shell wall can be realized with control to better than 1  $\mu\text{m}$ .

Two approaches to fabricating nested structures such as that shown in Fig. 1 have been considered. Both approaches lead to the production of spherical pellets by joining pairs of hemispherical shells, and both share a common first step--the formation of cavities in silicon by isotropic etching. A silicon wafer is oxidized at 1200°C in wet oxygen, forming a layer of silicon dioxide approximately one micrometer thick. Chromium and gold are next evaporated onto the front wafer surface and are then selectively removed using optical lithography. A second photolithography is used to open windows in the exposed silicon dioxide. The double photolithography is employed to minimize pinholing. The silicon wafer is next subjected to an isotropic etch consisting of 90 percent nitric acid and 10 percent hydrofluoric acid [7] under continuous agitation for the time required to form the desired hemispherical shape. The etch rate in this etchant is agitation dependent and is about 10  $\mu\text{m}$  per minute at room temperature.

Two factors are of primary importance in determining the quality of the hemispheres obtained using this procedure. First, the size of the opening in the silicon dioxide-chromium-gold etch mask relative to the desired cavity must be chosen carefully. If the opening is too large, the cavity will have a flat bottom, appearing bathtub-like rather than hemispherical. If the etch window is too small, it will not be possible to move etchant in and out of the cavity satisfactorily. A window size equal to about 25 percent of the final diameter after etching has been found to result in well-defined hemispherical cavities.

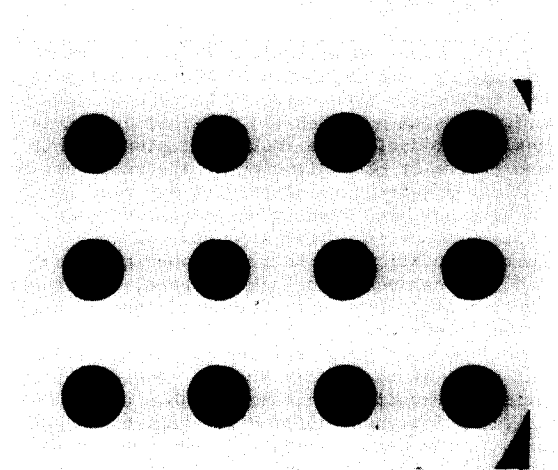
The second factor determining the quality of the hemispheres is the agitation method. Since this etch is rate-limited by the transport of HF to the silicon surface [7], and since a relatively large amount of silicon must be removed through the small mask opening, the agitation should be vigorous and the etchant velocity should be uniform and normal to the wafer surface.

Proper selection of etch-window diameter plus vigorous agitation of the etchant results in the creation of well-defined hemispherical cavities (of nearly constant radius and excellent surface finish). For example, Fig. 2a illustrates a 2-dimensional array of such cavities etched in the central portion of a two-inch wafer. The uniformity of the etched cavities is apparent in Fig. 2b, which is a magnified view of one small section of the array. Careful examination of this wafer

revealed that the cavities were smoothly etched and nearly hemispherical.



(a)



(b)

FIG. 2 HEMISPHERICAL CAVITIES IN SILICON. (a) TWO-DIMENSIONAL ARRAY OF 200- $\mu\text{m}$  DIAMETER CAVITIES ETCHED IN THE CENTRAL PORTION OF A 2-INCH SILICON WAFER. (b) MAGNIFIED VIEW.

In one approach to pellet fabrication, the silicon cavities are used as molds to form pellet halves of various materials. For example, hemispherical shells of polymethylmethacrylate (PMMA) or metal can be realized as follows. The metal-and-oxide etch mask on the wafer is first removed and a thin layer of gold is evaporated onto the silicon cavities and

then electroplated to a thickness of 1 to 2  $\mu\text{m}$ . Next, a film of PMMA is spun on the wafer, coating the cavities. The PMMA dilution (in trichloroethylene) and spinning speed determine the PMMA film thickness. (The PMMA can be selectively removed between cavities at this stage, using a photolithographic operation to leave a flanged PMMA lining in the cavity.) Since gold has a low adhesion to silicon, the gold film can be easily lifted, taking with it the PMMA structures, which conform to the cavity shape. The gold can be etched away leaving flanged hemispheres of PMMA with wall thicknesses of 1  $\mu\text{m}$  or less.

The molding technique just described has two primary advantages. First, since the silicon mold is used nondestructively and can be used repeatedly, great care and considerable expense can be justified to produce a high-quality structure. Second, this method can be used to produce pellets from a wide variety of materials, including metals, glasses and plastics, which can be evaporated, sputtered, plated, spun, or otherwise deposited in thin uniform layers. Also, it should be relatively simple to produce multilayer pellets using this approach.

A second approach to producing pellet structures from etched silicon cavities involves the use of etchants whose etch rate is sensitive to doping in the silicon. In particular, the etchant ethylene diamine-pyrocatechol (EDP) [8] is sensitive to the amount of boron in the silicon crystal. The etch rate drops nearly to zero for boron levels exceeding about  $5 \times 10^{19} \text{ cm}^{-3}$  (about 0.1 percent boron in the silicon lattice). This method is shown in Fig. 3. The Cr/Au etch mask for the cavities is first removed and the silicon is exposed both in the cavity and in a narrow ring, or flange, around the cavity rim. The remaining oxide acts as a mask when high concentration of boron is introduced into the exposed silicon via high-temperature diffusion. After this doping step, the oxide is stripped and the boron layer, a boron-doped single-crystal silicon shell having the shape of the initial cavity and flange remains following the etch. The wall thickness can be precisely controlled by controlling the time and temperature of the diffusion. Figure 4 shows a flanged hemisphere of silicon produced by this technique.

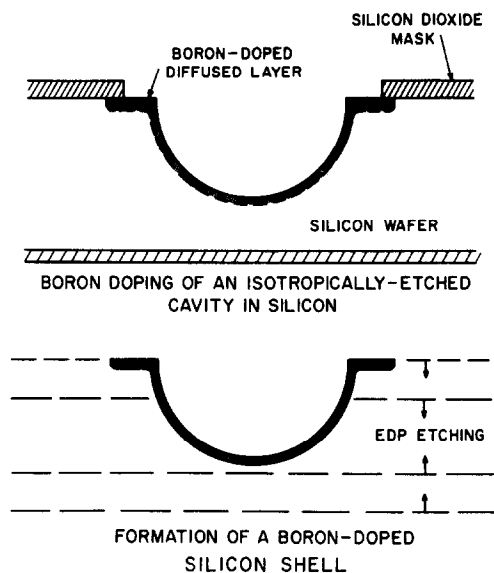


FIG. 3 FORMATION OF BORON-DOPED SILICON HEMISPHERICAL SHELLS.

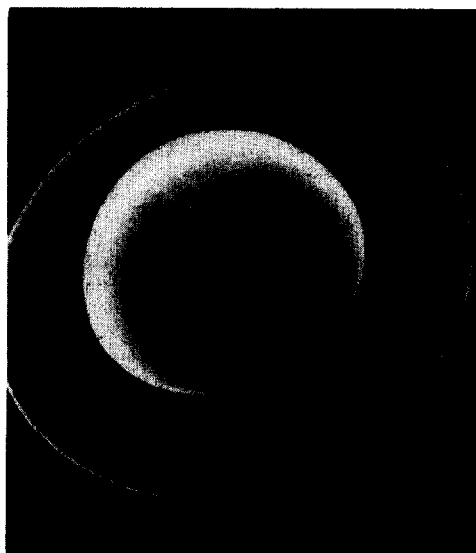


FIG. 4 FLANGED SILICON HEMISPHERE. THE DOME HAS A DIAMETER OF ABOUT 325  $\mu\text{m}$  WITH A WALL THICKNESS OF 2.5  $\mu\text{m}$ .

Data on the silicon hemispheres produced to date have indicated that surface features (roughness) on the inner (concave) and outer surfaces are less than 300 and 1000 Å, respectively. On a given wafer, eighty percent of the hemispheres produced have had diameters within 1.5 percent of the average, exhibiting equatorial cross sections which are circular to better than two percent. Sphericity to within two percent has also been achieved, although the control and reproducibility possible for this parameter has yet to be studied. Wall thickness should be reproducible to better than 1000 Å.

Spherical pellets can be achieved by aligning the hemispherical cavities of two identically processed wafers and sealing them prior to the EDP etching step. The aligned wafers may be sealed electrostatically [9] or by other means. The joined wafers are etched in EDP until the undoped silicon has been dissolved leaving only individual hollow, boron-doped silicon pellets with flanges.

Nested pellet structures such as that shown in Fig. 1 can be realized using these techniques. For example, an inner sphere can be supported within a larger shell by placing it on a diaphragm stretched between the mating hemispherical cavities. To realize diaphragms of PMMA, a thin layer of gold is first evaporated onto a polished wafer after which a thin layer of PMMA is spun onto the gold layer. The wafer is then thermally joined to a second silicon wafer in which hemispherical cavities have been etched, sandwiching the PMMA/gold layer. Since evaporated gold has poor adhesion to silicon, the polished silicon wafer can be easily detached, after which the gold layer can be etched away leaving the PMMA film stretched across the etched cavities. If desired, circular holes or other patterns can be produced in the PMMA diaphragm by exposure to low-intensity electron beam. The pellet to be supported by the diaphragm can then be positioned at the desired location. For example, Fig. 5 illustrates a diaphragm stretched across a hemispherical cavity and supporting a small pellet. The internal fuel pellet can be "bonded" to the diaphragm or held between two diaphragms stretched across mating hemispherical cavities. As experimental requirements evolve to include larger pellets, the flanges described and depicted can be made negligibly small; in fact, the wall itself may present an adequate sealing surface.

### 3. CONCLUSIONS

The proposed fabrication techniques are capable of producing inertial confinement fusion pellets from a variety of materials in a variety of configurations. The potential for mass production can be appreciated by noting that a single four-inch silicon wafer can yield as many as 100,000 250- $\mu$ m pellets. If processing costs are assumed to be comparable with those for integrated-circuit processes, the economic advantages are apparent.

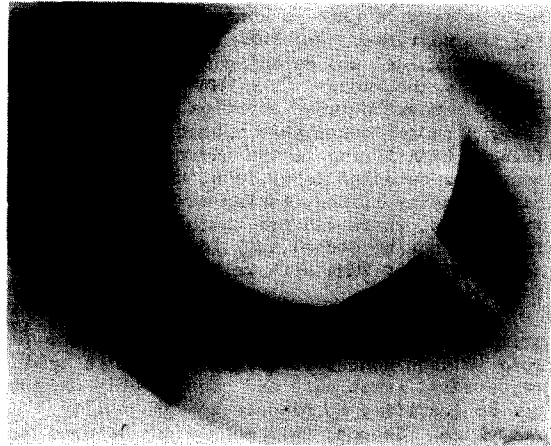


FIG. 5 SMALL PELLET SUPPORTED BY A PMMA DIAPHRAGM STRETCHED ACROSS A HEMISPHERICAL SILICON SHELL.

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