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LASER AND PARTICLE GUIDING MICRO-ELEMENTS FOR PARTICLE ACCELERATORS*

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Abstract

Laser driven particle accelerators require sub-micron control of the laser field as well as precise electron-beam guiding so fabrication techniques that allow integrating both elements into an accelerator-on-chip format become critical for the success of such next generation machines. Micromachining technology for silicon has been shown to be one such feasible technology in PAC2003[1] but with a variety of complications on the laser side. However, fabrication of transparent ceramics has become an interesting technology that could be applied for laser-particle accelerators in several ways. We discuss the advantages such as the range of materials available and ways to implement them followed by some different test examples we been considered. One important goal is an integrated system that avoids having to inject either laser or particle pulses into these structures.

INTRODUCTION

Recently, laser-driven particle acceleration in vacuum was demonstrated [2]. The main objective of that first, proof-of-principle experiment was to verify the validity of the method and to study its physics. Now it is practical to pursue the design of higher gradient and impedance geometries such as photonic bandgap structures [3, 4].

Dielectric materials appear well suited for laser-driven accelerator structures. They are used in transmissive elements for discrete, macro-optical elements such as lenses and prisms but also in micro-chip compatible objects having sub-wavelength features. Dielectric coatings for filters or high reflectors, optical waveguides and photonic bandgap fibers are other examples. However, while the technology for micro-optics is developing rapidly, it is mostly geared for telecom applications and, due to the radiation environment and the required high peak power, the technology cannot be transferred directly and needs specific development.

In previous years we studied Silicon as a candidate material. In addition to its radiation resistance and abundance, low cost micromachining techniques that allow easy fabrication of sub-micron features. Another useful aspect is its high thermal conductivity, important for effective heat removal. Finally, it has a wide transparency range in the near- to mid-infrared that is ideal for 2 mm or higher wavelength sources such as Cr:SnSe, Tm:YAG or down-converted Nd:YAG or Yb:YAG where it shows no absorption and features a high index of refraction.

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Here we consider the possible uses of ceramics to help provide an AOC e.g. rare-earth, doped or undoped YAG and various intermetallic, magnetic materials such as Fe_xCo_{1-x} or $SmCo_5$ but first we begin with a general discussion of ceramics and relevant research in this field.

CERAMICS – STATUS&POSSIBILITIES

With ceramics, the materials, their composition and their temperature characteristics are all important as is their subsequent cooling used to produce an incredible variety of different physical structures. While there is a range of different classes of materials, we concentrate on two that are especially interesting for our applications beginning with transparent, electroptic possibilities followed by magnetic, intermetallic compounds.

The electrooptic materials and processing toolkit applied to laser gain media can allow spatial control of doping profiles and the index of refraction, optical quality bonding and the preparation of new host materials not available as bulk grown single crystals. These new materials open the possibility of improved optical quality, improved thermal control, gain and bandwidth control, and scaling to larger size laser gain media at a cost significantly lower than now available. Although commercial laser ceramics are only now beginning to emerge, transparent ceramics have been known since the 1950s. Early research was driven by nose-cones for heat-seeking missiles, sodium street lamps and fighter aircraft windows. The first commercialized transparent ceramic, called Lucalox, was introduced by GE in the 1960s. This transparent sapphire (alumina) ceramic is used because of its high fracture strength and high thermal conductivity.

Another example is a transparent ceramic called ALON (aluminum oxynitride). Stronger, harder and lighter than glass, ALON is available in half-inch-thick sheets up to 20 by 32 inches. This versatile material has many applications, including military vehicles, forward-looking windows on planes and missiles, windows for barcode scanners, and scratch resistant lenses.

An early ceramic laser was demonstrated in 1966 in $Dy:CaF_2$. Recent ceramic lasers include the very promising Cr_2+:ZnSe laser that operates in the 2.6 micron region. The quest to produce transparent oxide ceramics, like YAG, has proved to be a difficult technical challenge with the development of laser-grade transparent ceramics an even greater challenge, primarily because their performance requirements are significantly more stringent than the requirements for window applications. In

transparent ceramics, scattering is the greatest loss mechanism originating from a number of sources, including pores, grain boundaries, compositional gradients within individual grains, as well as optically anisotropic material phases and lattice imperfections that can cause local index variations. Only in the last decade has the technology of transparent oxide ceramics matured to the point where losses have been reduced enough to achieve laser performance rivaling that of single crystals.

Intermetallic compounds are defined as mixtures, in specific proportions, of two metallic elements that form a crystalline structure differing from the original elements e.g. FeCo. They have high melting points, good strength but poor ductility resembling ceramics. However, they reflect well due to their metallic lustre, conduct heat and electricity well and are made via powder metallurgy, similar to ceramics. When heated to their transition temperatures, well below their melting points and cooled, they exotherm to compact but are brittle at room temperature and extremely difficult to machine even with EDMs. This technology is developing but seldom applied except for a few, notable, rare-earth, transition metals (RETM) such as $SmCo_5$, Sm_2Co_{17} or $Nd_2Fe_{14}B$.

While such rare earths are not especially rare for their masses, they tend to have lower melting points (and Curie temperatures T*c*) than the important transition metals even though their individual magnetic moments per atom are much higher. Further, they have little or no bulk saturation magnetization M_s at room temperature whereas Fe and Co are extremely strong with very high T_c at room temperature. This explains the tendency to combine these two groups in the combinations above to emphasize their individual advantages. To make magnets from such materials, another important characteristic is the coercive force H_c or the ability to resist demagnetization in external fields. We approximate this as:

$$H_c \approx \frac{1}{R}\sqrt{\frac{kT_c K_1}{\alpha M_s}}$$

with K_1 the magneto-crystalline anisotropy energy and R the grain radius. Small admixtures of REs are explained from K_1's proportionality to the magnetic moment.

Current research uses composition and crystal structure to achieve a balance between H_c and M_s – both of which we want to maximize. Progress has been slow so that the RETM compound with the largest M_s and good H_c has a low melting point and low T_c of 310±C compared to FeCo(50%) with a 1500°C melting point and T_c approaching 1000° or roughly the average of its two components. We note that both Fe and Co have higher melting points than Si which is above 1400°C. Thus, this seems an ideal area to integrate ceramic techniques, integrated circuit techniques and materials research for micro-magnets such as planar undulators for many applications but specifically to help micro-bunch low energy electrons for laser accelerators.

SOME EXAMPLES

We have made many etching tests to verify and understand previous work and to extend it for our applications. Masks usually include several structures over a range of scales to test different etchant and mask conditions. While one can usually discriminate outcomes with an SEM, it is difficult to capture good photos of the smaller, deeper feature sizes, e.g., 5-20 μm wide through-slits in a 500 μm thick wafer. Figures 1-2 show some gratings such as used for ceramics tests. In this and similar SEM pictures, we have shown[1] that it is possible to go from an unknown [111] orientation on a (110) wafer to make small accurate slits with length-to-width ratios of 250:1 and wall height-to width ratios of 500:1. We also demonstrated that the surface of the walls were flat, parallel and smooth to better than ~10 nm by finding and focusing on particles < 100 nm in size on the wall surfaces. By loading these with intermatallic nanoparticles we expect to produce a true micro-undulator. Thus, rather than conventional use of Si technology we will attempt to develop a hybrid technology incorporating ceramic techniques.

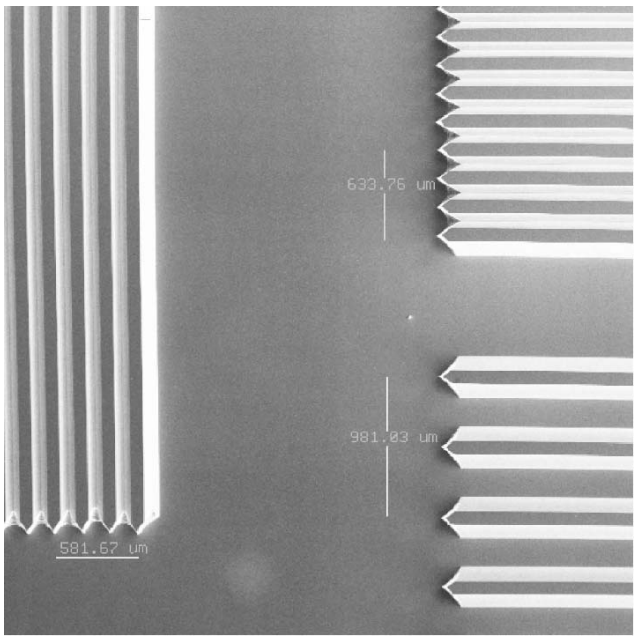

Figure 1: Different period structures printed on Si and cut for use as preforms for ceramic structures.

Figure 3 shows a ceramic YAG grating structure similar to the Si grating in Figure 2. This structure was fabricated by using a silicon grating as a preform.

Planar Undulators are also possible to integrate as micro-elements for particle accelerators and can be fabricated with common lithographic techniques [1]. We have studied various coil-dominated fields and the hardest aspect is not to fabricate or excite them but to measure the

Figure 2: View of a 500 µm grating etched on (100) Si.

Figure 3: Stripes of YAG nanoparticles imprinted with Si gratings such as shown in Figures 1-2.

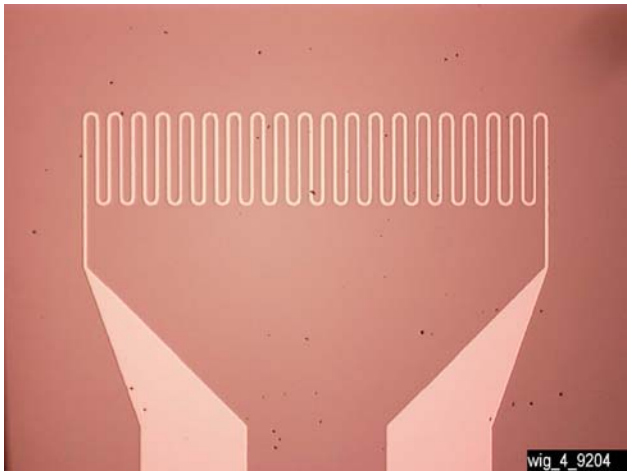

Figure 4: Typical Au on Si undulator circuit

fields. Using gold, many undulator patterns were produced on both quartz and Si wafers that have been driven with 1 ns pulse currents up to several amps without failure by careful conditioning to higher currents. To accommodate particle beams, periodic trenches and slits are needed. These can be used as pattern generators. We have shown they can be made as deep as the full wafer thickness [1] with widths of 15-2000 µm.

SUMMARY

We have explored existing micro-fabrication techniques that we ultimately aim to adapt to fabricate an on-chip laser-driven particle accelerator structure that integrates both the laser field guiding elements and the magnetic focusing elements. Our initial work included anisotropic etching techniques for silicon that allowed us to produce very deep and narrow channels that are potentially suitable for particle guiding. Furthermore, this etching technique allowed us to produce flat tilted surfaces at very specific crystal orientations on silicon that can serve as high reflector or Brewster interfaces of optical quality. More recently we have begun exploring micro fabrication techniques on ceramic materials that will allow us to integrate both the optical and the magnetic guiding elements in a natural fashion. We have made initial tests of stamping micro-features on ceramics with a simple silicon preform and plan to refine this technique in the near future. Also we plan to explore magnetic ceramic materials and methods to integrate these with optical ceramic materials to an integrated structure.

CONCLUSIONS

The presence of a radiation environment, the need for vacuum compatibility and the sub-micron precision requirements for a future laser-driven particle accelerator present an interesting technology challenge whose successful development may find use in other fields such as space based applications. Our unique requirements suggest new materials science questions and make this an important research area in its own right.

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