FABRICATION OF A LASER-BASED MICROSTRUCTURE FOR PARTICLE ACCELERATION*

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Abstract

The Micro-Accelerator Platform is an optical-wavelength microstructure for laser acceleration of particles, currently under development at UCLA. It is a slab-symmetric structure and can be constructed in layers using existing nanofabrication techniques. We present several possible fabrication techniques and preliminary experimental outcomes for manufacturing this structure.

INTRODUCTION

Laser driven dielectric accelerators have been under investigation at UCLA since 1995[1], with extensive theoretical analysis and simulation results reported [2] [3]. A simplified metallic test structure has been made and tested [4]; however, results on fabrication of a proof-of-concept all-dielectric device, and tests of such a device, have been lacking. Recently, with the development of high-power lasers and progress in nanotechnology, building actual structures at the wavelength scale and making tests on them has become possible.

The all-dielectric accelerator structure has been described in previous work [3], and consists of Distributed Bragg Reflectors (DBR), and periodic diffractive slots on the outer surface. Such a device can be fabricated in a cleanroom using various nanolithography and thin film deposition techniques. It is worth to mention that the fabrication techniques can have an important impact on the device performance. For example, different thin film deposition methods and process parameters can result in different material refractive index, film uniformity, etc. This work presents the first experimental results toward building an all-dielectric accelerator, by comparing different thin film deposition and nanolithography techniques, establishing a tentative manufacture process for the accelerator structure.

EXPERIMENTAL RESULTS

The fabrication of the device is being carried out in UCLA's nanofabrication facility. Since the resonant wavelength chosen based on an available laser is 800nm, we require material optical transparency at 800nm. In addition, good thermal conductivity and stability, mechanical strength and high breakdown limits are also desirable. We choose sapphire as the substrate, ZrO_2 as the high index material, and SiO_2 as the low index material, with numerical simulation results for this structure presented elsewhere at this conference [5]. To simplify the experimental optimization process, test runs are carried out on Si substrate instead of sapphire, taking advantage of the wafer-scale processing. The dielectric DBR and the slots are fabricated separately for the test runs.

Distributed Bragg Reflector

The DBR is made from dielectric thin films with high contrast in refractive indices, e.g. ZrO_2 and SiO_2. Both of them have excellent thermal and mechanical properties as well as high laser induced damage threshold (LIDT), making them ideal for high power laser DBRs [6][7]. Such thin films can be deposited using atomic layer deposition (ALD), sputtering, or evaporation. As ALD can control the film thickness and uniformity on the atomic scale, and has high film density and low impurity level, it is a good candidate for depositing high-index materials. Its main limit lies in its long process time and more elevated cost. Evaporation is a relatively cheap and fast technique used for thin film deposition; however, when it comes to compounds, the film composition often deviates from the ideal due to target decomposition. Sputtering, on the other hand, maintains the composition of the target as well as producing good film quality at reasonable speed. In this work we use a sputtering technique for all the thin film depositions.

The depositions are conducted with a Denton Discovery 550 sputtering system using a RF power source. The RF power level plays an important role in determining the deposition rate and film quality of the material, with high power having a faster deposition rate, but larger gain size and less film uniformity. Fig. 1(a) shows ZrO_2 thin film deposited with 300W RF power, where the thin film has poor adhesion to the substrate, showing a dome structure with diameter ranging from a few microns to hundreds of microns. Fig. 1(b) shows the film obtained with 200W RF power, showing a uniform film with grain size tens of nanometers. The refractive index of the thin film, as measured by ellipsometry, is 2.17 at 800nm.
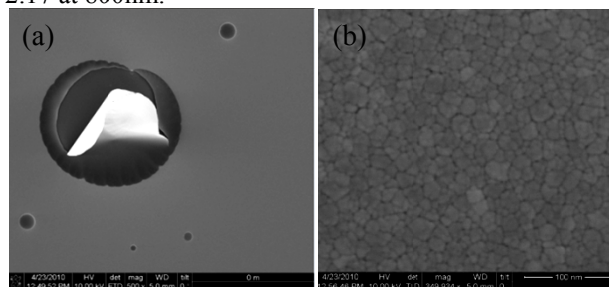

Figure 1: SEM micrographs of ZrO_2 thin film deposited by sputtering. (a) RF =300W, thin film detaching from substrate; (b) RF = 200W, uniform thin film obtained.

SiO_2 thin film is deposited by the same sputtering system with RF power of 400W. The film is very uniform with homogeneous grain size, as shown in Fig. 2. The grain size of the SiO_2 film is smaller and more homogeneous compared to the ZrO_2 film. The refractive index of the film measured by ellipsometry is shown in Fig. 2. At the wavelength of interest, 800nm, the index is 1.455.
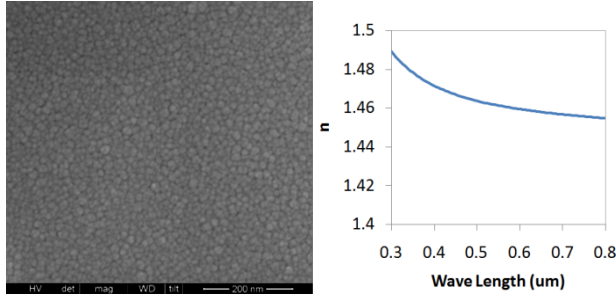

Figure 2: Homogeneous SiO_2 thin film deposited by sputtering at RF = 400W. Left image is SEM micrograph, right graph is refractive index measured by ellipsometry.

Coupling Slots

Theoretical study has shown that the coupling slot periodicity has to be equal to the laser wavelength of 800nm, and numerical simulation has optimized the slot size to range from 100nm to 300nm. At this scale, both electron beam lithography (EBL) and focused ion beam (FIB) milling are options to produce the desired patterns. Here we report results of these two approaches.

Electron Beam Lithography

We use a Vistec EBPG 5000+ES system which operates at 100kV, with 5nA beam current to make the pattern in poly(methyl methacrylate) (PMMA). Subsequent to the EBL, the pattern is transferred into a dielectric layer using a lift-off technique. Fig. 3 shows the pattern in PMMA with slot width 200nm.
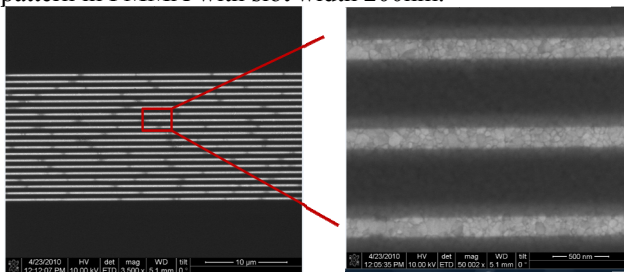

Figure 3: SEM images of nano-slots patterned in PMMA

After PMMA patterning, a dielectric thin film is deposited by sputtering, followed by a 10-min lift-off in acetone. Most of the thin film is successfully lifted off, however, at the nano-slots area, lift-off is not successful, as shown in Fig. 4. The dielectric thin film is stripped off at the surrounding areas, but at the slots, the thin film breaks off from the surroundings, and remains as a whole piece, instead of individual lines only in the slots. This is possibly caused by deposition on the sidewalls of the slots, which forms a continuous layer and strongly adheres to the substrate. Solutions to avoid sidewall

deposition include using evaporation deposition or adopting bilayer lithography to create an undercut along the sidewalls.
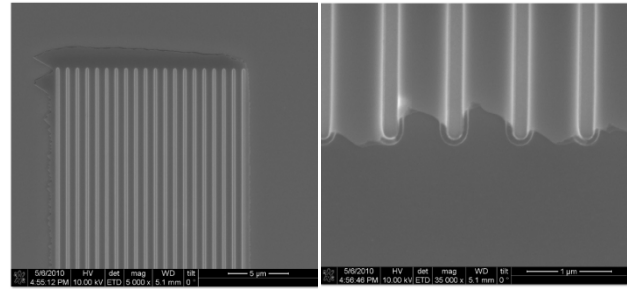

Figure 4: Lift-off problem at the nano-slots area. Most of the sputtered SiO_2 film is stripped, but the slots area is still covered. Right image shows the partial stripping at the end of the slots.

Focused Ion Beam Milling

A focused ion beam can be used for direct dry etch of literally any material, producing nanoscale patterns in them. Here we first deposit the dielectric thin film SiO_2 on a silicon substrate, and then use FIB to etch slots in the film, and eventually fill in the slots with high index material. By using this process we eliminate the need of a lift-off process, which is challenging at the nano regime. It is also worth to mention that this process reduces the number of wet processing steps, and thus reduces potential contamination from liquids and containers. This cleaner process promises higher film quality and better overall device performance.

A FEI Nova 600 FIB machine with acceleration voltage 30kV is used for the milling. The ion beam current is selected to balance between process time and pattern resolution. The beam current used here is 50pA, and the process time is about 3 min for 10 lines. SEM images of the patterned slots are presented in Fig. 5, showing slot width of about 50nm. Compared to EBL results, the FIB lines have smaller critical dimensions, and have better defined line edges.
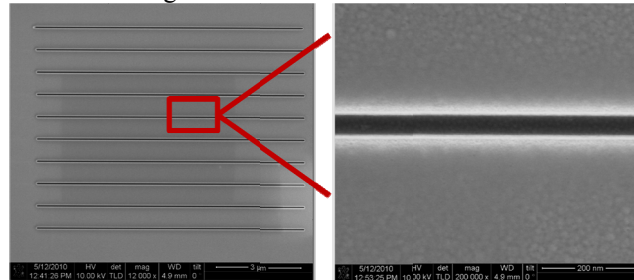

Figure 5: Slots patterned by dry etch using FIB, showing line width of 50nm.

To examine the sidewall profile, after FIB milling, Pt is deposited by ion-beam evaporation to a thickness of 300nm, to conserve the sidewall profile of the slots. Then a high voltage ion beam is used to cut through the Pt film and underlying slot structure to make an opening. Cross-section images of the slots, taken at 52º tilt, are shown in Fig. 6. The sidewalls are fairly straight, although at the

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bottom there is a curve, with the center being etched the most. The impact of the curved structure at the bottom, on the efficient coupling of the electromagnetic field into the vacuum gap, will need to be investigated in future simulations and experiments. A potential problem with FIB machining is that for manufacturing the actual device, the writing area is about 1cm×1cm, leading to a very long writing time. In addition, to cover such a large area, the sample stage has to be moved physically, which will cause serious stitching error. Despite the potential problems for manufacturing, FIB is still a good option for building simplified proof-of-concept prototypes.
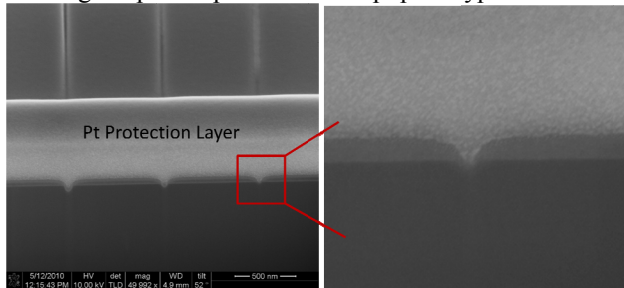
Figure 6: Cross section images of the FIB-milled slots in SiO_2 on Si substrate. Images taken at 52º tilt.

CONCLUSION

Experimental efforts have been made toward making a prototype micro-accelerator device. The distributed Bragg reflector is made using sputtered dielectric thin films ZrO_2 and SiO_2, and coupling slots are fabricated using both electron beam lithography and focused ion beam milling. Attempts to solve the lift-off problem with EBL will be made by using evaporation instead of sputtering in the future, and FIB is only suitable for building simplified small structures, not ideal for manufacturing actual-dimension devices. Future work includes integration of the slots with DBR, and accurate alignment of electron source with the vacuum gap of the accelerator structure.

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