FABRICATION OF MIRCO-SCALE METALLIC AND DIELECTRIC ACCELERATOR STRUCTURES WITH SUB-WAVELENGTH FEATURES*

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Abstract

The millimeter-scale Micro Accelerator Platform (MAP)–essentially a "particle accelerator on a chip"- will allow for revolutionary medical and industrial applications due to its manageable size and reproducibility. The MAP consists of an electron source and an all-dielectric, laser-powered accelerator. The dielectric structure has two slab-symmetric reflecting mirrors with a vacuum gap between them, and periodic coupling slots allow laser power to enter transversely through one mirror. This mechanism is analogous to the slots of an optical diffraction grating, with coupling period and vacuum gap equal to the wavelength of the laser (800 nm in this study). Work to date includes design, fabrication and testing of a prototype relativistic structure using a patterned gold layer. In addition, we have studied fabrication techniques and the electromagnetic design of an all-dielectric (non-metallic) structure. Fabrication of the final structure is modelled after Vertical-Cavity Surface-Emitting Lasers (VCSEL) and Distributed Bragg Reflector (DBR) layering techniques. Preliminary numerical studies of the sub-relativistic structure are also presented.

INTRODUCTION

Conventional accelerator cavities are powered by long-wavelength RF, proportionally determining their size [1] and limiting their accelerating gradients due to electric breakdown [2]. A sub-micron, all-dielectric particle accelerator like the Micro Accelerator Platform (MAP) could fit entirely onto a disposable micro-chip [3], allowing innovative industrial and radiation therapy applications due to its size, efficiency, and reproducibility.

The MAP is powered by laser, potentially through a fiber optic cable. In addition to a self-contained electron gun, the design is characterized by a micro-scale, all-dielectric, accelerating structure comprised of two parallel, slab-symmetric, all-dielectric reflecting mirrors separated by a vacuum gap. The laser (800 nm in this study) enters through a periodic coupling mechanism in the upper mirror that serves as a diffractive optic. The vertical width of the vacuum gap and period of the coupling mechanism are equal to the laser wavelength. The dielectric materials and periodic coupling allow for resonant increase of high amplitude, periodic electric fields with high breakdown threshold [4].

*Work supported in part by the UCLA office of the Vice Chancellor of Research, by the Dean of Physical Sciences, and the Department of Physics and Astronomy. Additional support was provided by the Undergraduate Research Center-Center for Academic and Research Excellence (URC-CARE). Supplemental funding was also provided by the US Department of Energy.

PROTOTYPE METAL STRUCTURE

Prior to the fabrication of the all-dielectric structure, it was desired to create a simplified, cold-test structure. A prototype using metallic boundaries was designed and fabricated. Simulations were used to confirm that a finite resistivity, metallic (gold) structure would produce fields similar to those expected from the ideal models. Critical considerations in the fabrication of the metal structure include substrate selection and preparation, metal deposition, and fabrication of the periodic coupling mechanism.

The substrate serves to mechanically support the structure. Fused silica and sapphire transmit at 800 nm and have lattice structures compatible with gold. A smooth substrate guarantees the vacuum gap has laser-wavelength width regardless of the gold deposition quality. Gold deposition by sputtering or evaporation, which control the uniformity and total thickness of the gold across the substrate, ensure fabrication of effective coupling slots. Further, in the metallic model, the coupling strength is determined by the slot height which is equal to the metallic layer thickness. A sputtering method developed empirically by a UCLA colleague, S. Prikhodko, creates a gold layer approximately 80 nm thick.

A Focused Ion Beam (FIB) milling apparatus at UCLA was used to produce the periodic coupling mechanism by cutting grating-like slots (Fig. 1) in the gold layer that have laser-wavelength spacing. The ~25-slot cutting pattern is sequentially applied to obtain a structure with about 200 slots, enough to capture a measurable amount of light. An SEM is used in conjunction with the FIB to image the structure during the milling process.

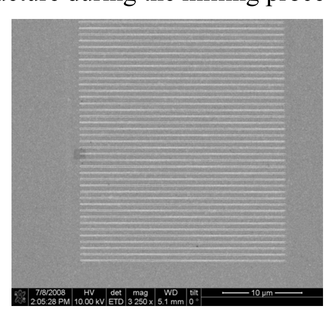

Figure 1: Coupling Mechanism for metal test structure.

Two metal test structures are fabricated: one sputtered with 80 nm-thick gold onto 10mm of sapphire, the other evaporated with 160 nm-thick gold onto 300 µm of fused silica. The dimensions of each structure are approximately 21x160 µm. The quality of the deposition and achieving correct gold-layer thickness limits the efficiency of the structures.

The interferometric diagnostic was not able to observe a measureable resonance (results detailed in Ref. [5]). The performance of the fabricated test structures may be limited by properties of thin gold and non-uniformity in the coupling slots and deposition thickness. A number of shortcomings in the prototype fabrication are detailed in Ref. [6].

ALL-DIELECTRIC STRUCTURE

The metallic prototype can only serve as a cold-test model. In order to measure realistic field properties and achieve high accelerating gradients, an all-dielectric structure must be fabricated. Considerations for the fabrication of an all-dielectric accelerating structure (Fig. 2) include substrate selection and preparation, dielectric layering to create the vacuum gap and periodic coupling mechanism, and modifications to allow for sub-relativistic acceleration. Techniques considered include Distributed Bragg Reflector (DBR) materials and Vertical-Cavity Surface-Emitting Lasers (VCSEL) fabrication methods, which control deposition and dielectric layering on the sub-micron scale.

The results of the initial design effort and fabrication method survey, for the considerations delineated above, are presented in the sub-sections below.

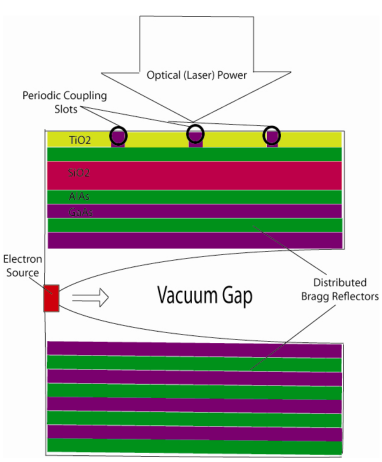

Figure 2: Schematic of the all-dielectric structure.

Substrate and Material Selection

The substrate must provide an optically flat, mechanically rigid, and highly transmissive platform. A number of materials were considered including fused silica, sapphire, CVD diamond and silicon carbide [7, 8]. However, in order to grow epitaxial layers, a GaAs substrate is likely required. A flat substrate maintains an accurate vacuum gap. Fluid Jet Polishing can smooth surface roughness within 5 nm over the entire surface (unlike mechanical polishing).

Additional materials and their properties were studied. The dielectric reflectors are comprised of Gallium and Aluminium Arsenide (GaAs and AlAs), which have a reasonable low-high index of refraction gradient (3.0–3.7) and compatible crystal lattice structures for layer-by-layer growth. Molecular Beam Epitaxy (MBE), in which a slow evaporation process in a vacuum heats materials to the form GaAs or AlAs layers, can effectively create DBRs with layers of alternating material [9]. Silicon Oxide (SiO_2) and Titanium Oxide (TiO_2) allow for periodic coupling.

Fabrication of Vacuum Gap

To fabricate a monolithic structure (e.g. top and bottom slabs as part of a single structure), methods of creating cavities were examined. VCSEL fabrication methods, including air-post etching, ion-implantation, etching and re-growing, or selectively oxidizing, create laser cavities between DBRs that are analogous to the vacuum gap of our structure [9]. The etched air-post method lacks the process control to achieve small feature size. Ion-implants can be deposited into the DBR above the laser cavity to define the transverse extent of the cavity, but these implants do not have applications relevant to our structure. The etching and regrowth method requires etching an air-post and epitaxy to define the DBR layers. Selective oxidation rates of materials (particularly Aluminium) are very difficult to control and require high temperatures; Reactive Ion Etching (RIE) creates holes that expose oxidation layers, whose lateral oxidation is determined by the materials and length of oxidation of the layers. An aperture allowing light to enter the laser cavity forms through the overlap of oxides near the holes.

Fabrication of Periodic Coupling Mechanism

In addition to the substrate and DBR layers, the MAP requires a patterned diffractive optic which acts as a coupler and enforces the accelerating mode. Approaches to fabricating this challenging sub-wavelength pattern were studied.

A review of existing methods indicates that near-field optical lithography can produce the ~200 nm feature sizes required for the MAP coupler. Laser Interference Lithography (LIL), in which a standing wave pattern is produced by a laser and imprinted onto a photoresist layer [10], can generate the ~1000 periods desired for the MAP without the need for costly mask production.

THE SUB-RELATIVISTIC STRUCTURE

Ultimately, it is desired to have the MAP accelerate particles from capture energy (~ 25 KeV) to relativistic energies. The structure must therefore be adjusted from ß ~ 0.3 to relativistic (ß ~ 1) velocities. The period of the coupling structure will have to vary as ßλ (with implications in the fabrication method). Moreover, matching the structure phase velocity to that of the accelerated particles will require either variation of the gap (tapering) or variation of the inner dielectric layer properties. Practically, accomplishing this and simultaneously preserving an electric field pattern in the vacuum gap similar to that of the prototype (Fig. 3) requires varying both the gap height and optical properties of the dielectric layer across several periods. Tapering the layer of GaAs just above and below the vacuum gap allows the structure to resonate at a larger period for small ß and at increasingly shorter periods for

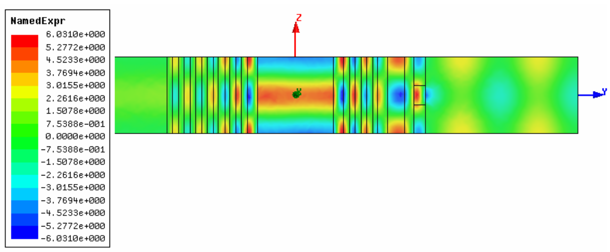

Figure 3: Field generated by prototype all-dielectric structure with a relative intensity scale (resonance: 375.2Thz). The laser enters horizontally from the right.

larger ß, thus matching the structure period to the changing period as viewed in the electron reference frame.

A numerical study is being undertaken to see if variation of the inner matching layer could be accomplished using 2 materials or material-vacuum combinations. The modified structure design includes 4 equally spaced, low permittivity gaps (e.g. air) in the GaAs layer just above the vacuum gap; this mixing of high and low permittivity reduces the average permittivity of the layer across the length of structure. A higher average permittivity reduces the structure beta. We keep the average permittivity of the layer near that of GaAs (13.396) to maintain the resonance achieved in the prototype (Fig. 3) using HFSS to generate field simulations with different combinations of materials. High/low permittivity combinations produce fields (Fig. 4) similar to the original model, but the fields "bow" near the center of the vacuum gap. There is also a high level of saturation along the axes of the air gaps, which we unsuccessfully attempt to reduce by doubling the number of gaps to 8. Further simulations, using different permittivities and arrangements of materials, are necessary, but reducing β may require more thorough modifications to the structure. Tapering combined with permittivity variation may achieve the dynamic range required to vary β from 0.3 to 1.

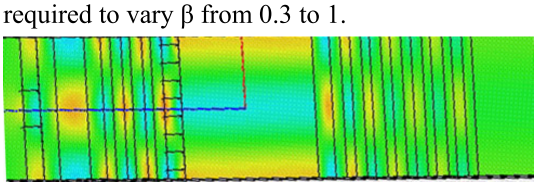

Figure 4: Fields generated by modified all-dielectric accelerating structure using GaAs and AlAs with a relative intensity scale (resonance: 374.6Thz). Laser enters horizontally through right side.

CONCLUSION

GaAs and AlAs layer growth using MBE is practical, but requires introducing positive (p-type) or negative (n-type) dopants. TiO_2 and SiO_2 are rarely grown with GaAs and AlAs due to exceedingly high temperatures required to grow these oxides. The original all-dielectric structure (Fig. 2) is being modified to exclude the oxides, and further research is necessary to select materials that will preserve the periodic intensity of the electric fields necessary for the MAP.

Successful steps taken in the creation of the MAPs all-dielectric and metal test accelerating structures include complete preparation and fabrication of two metal test structures and a plan for the preparation and fabrication of the all-dielectric structure based on DBRs and VCSELs. Efforts to improve precision control during substrate preparation and metal deposition are necessary to create resonant metal test structures. Preliminary research of the preparation and fabrication methods that create the dielectric structure verify a structure modelled after VSCELs and DBRs is possible, although further research is necessary. Ultimately, the size, efficiency, and reproducibility of the MAP may revolutionize the world of health care by enabling patient-friendly radiation therapy.

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