

# ADVANCES IN CVD DIAMOND FOR ACCELERATOR APPLICATIONS\*

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## Abstract

Diamond is being evaluated as a dielectric material for dielectric loaded accelerating structures. It has a very low microwave loss tangent, high thermal conductivity, and supports high RF breakdown fields. We report on progress in fabricating chemical vapor deposited (CVD) diamond materials for cylindrical dielectric structures for use in wakefield particle accelerators. Tubes with inner diameters of 5 mm have been grown from polycrystalline CVD diamond on mandrels using microwave plasma assisted CVD. The material has been laser trimmed to the desired thicknesses and lengths. In addition, rectangular (planar) dielectric structures have been constructed from plates of polished CVD diamond. Wakefields in these structures have been studied at the BNL Accelerator Test Facility. A wakefield breakdown test of a single crystal diamond-loaded rectangular accelerating structure has been carried out at the Argonne Wakefield Accelerator as well.

## INTRODUCTION

Diamond has been proposed as a dielectric material for dielectric loaded accelerating (DLA) structures [1-3]. Dielectric Loaded Accelerator structures using ceramics or other materials and excited by a high current electron beam or an external high frequency high power RF source have been under extensive study for many years [4-7]. Low loss microwave ceramics, fused silica, and CVD polycrystalline and single crystal diamonds [11] have been considered as materials for dielectric based accelerating structures to study of the physical limitations encountered in developing field strengths  $> 100$  MV/m at microwave [4-6] and  $> 1$  GV/m at THz frequencies in a dielectric based wakefield accelerator [6,7,11,12]. THz radiation has been generated recently by a short  $\sim 10$  GV/m pulse within a  $100 \mu\text{m}$  diameter quartz fiber [7]. A planar diamond-based DLA structure was proposed and studied recently by Omega-P, Inc., where the dielectric loading of this structure was to be made of diamond slabs fabricated using CVD (chemical vapor deposition) technology [2].

Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material will allow demonstration of high accelerating gradients; up to 0.5-1.0 GV/m as long as

the diamond surface can sustain a 0.5-1.0 GV/m short pulse ( $\sim 10$  ns) rf field without breaking down. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity ( $2 \times 10^3 \text{ Wm}^{-1} \text{ K}^{-1}$ ) and extremely low loss tangent ( $< 10^{-4}$ ) at Ka-W frequency bands. Secondary emission from the CVD diamond surface can be dramatically suppressed by diamond surface dehydrogenation or oxygentermination [3,6,8-12]. CVD diamond has already been successfully used on an industrial basis for large-diameter output windows of high power gyrotrons, and is being produced industrially in increasing quantities. The CVD process technology is rapidly developing, making the CVD diamond fabrication process fast and inexpensive. Given these remarkable properties, diamond should find numerous applications in advanced accelerator technology [3]. Euclid Techlabs collaborates with several companies and research groups on the development of cylindrical diamond structures. Planar diamonds are available commercially in various grades including single crystal diamonds. The goal of this research is to perform a wakefield acceleration experiment using a diamond loaded structure and to test diamond for breakdown. In this paper we report on progress towards diamond based DLA structures fabrication and our recent experiments with these structures at ANL/AWA and BNL/ATF.

## CVD CYLINDRICAL DIAMOND DLA STRUCTURE GROWTH

The cylindrical diamond dielectric tubes that are manufactured via a relatively simple and inexpensive chemical vapor deposition (CVD) process, plasma assisted CVD, have been considered in [3,6,11]. Our initial work was based on  $100 \mu\text{m}$  and  $5 \text{ mm}$  scale tubes with fundamental frequencies in the 0.1–1.0 THz range; promising results were obtained using the plasma assisted and hot-filament CVD process. Diamond is deposited when atomic hydrogen and carbon radicals react on a diamond surface held at approximately  $900^\circ\text{C}$ . For reasonable quality DVD diamond growth there is roughly 1 carbon atom incorporated for every  $10^6$  collisions of atomic hydrogen with the surface [14]. Consequently, the deposition rate can be slow, often less than  $1 \mu\text{m/hr}$ . Microwave plasma CVD, the process that is used in the bulk of our diamond manufacture has demonstrated one to two orders of magnitude higher deposition rates providing the atomic hydrogen flux is sufficiently high.

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Remarkably, under high flux of atomic hydrogen the diamond quality is very good even at these high rates.

Recently the 5 mm inner diameter, 2.5 cm long and 500  $\mu\text{m}$  thick high electronic quality “white” diamond tube has been fabricated for 35 GHz structure, Fig.1, and characterized with SEM, micro-Raman and micro-photoluminescence spectrum analysis [11].

## DIAMOND-BASED DLA STRUCTURES

The DLA structures come in different materials and shapes depending on the design. However, it is very challenging to shape and machine a material like diamond. Some sophisticated processes and tools have to be designed. Different assemblies of diamond based DLA structures smaller in diameter or rectangular in shape have been fabricated [9,10,12] originating from this idea. Fabrication techniques have been developed based on commercially available single crystal or polycrystalline high optical quality diamond plates.



Figure 1: Diamond cylindrical waveguide fabricated from CVD polycrystalline optical quality diamond.

Proof of principle experiments at BNL/ATF [9] have studied wakefields in diamond structures in the 250 GHz regime. The 3 nC, 30 micron beams that will become available from the new FACET facility at SLAC [6] will permit the demonstration of intense THz sources based on diamond structures. Figure 1 shows capillary diamond structures grown by CVD on an armature. Cylinders laser machined from a single crystal are shown in Figs. 2-3. These structures will be used at FACET and are remarkable as they consist of a single crystal. A laser cutting process is used to obtain the desired shape. The dimensions of these capillaries are 400/700 micron ID/OD and up to 10 mm in length.

The 5 mm radius, 500 micron white diamond structures (Fig.1.) mentioned previously are being used for experiments at the AWA [9]. In [10] the results of a wakefield breakdown test of single crystal diamond-loaded rectangular accelerating structure have been reported. The high charge beam from the AWA linac ( $\sim 70$  nC,  $\sigma_z = 2 - 2.5$  mm) was transported through a rectangular diamond - loaded resonator and induced an

intense wakefield [12]. A deep (200  $\mu\text{m}$ ) and narrow (20  $\mu\text{m}$ ) groove is cut on the diamond surface to enhance the field (by approximately a factor of  $\epsilon$ ). Electric fields at least of 0.3 GV/m were present on the diamond surface in the groove (decay time  $\sim 35$  ns). A surface analysis of the diamond was performed before and after the beam test. No breakdown-type damage was observed on scanning electron microscopy images [10].



Figure 2: Single crystal diamond structures laser machined from a CVD single crystal. (ID=400, OD=700 microns)

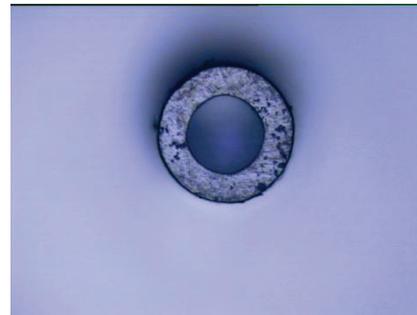


Figure 3: Cross sectional cut through one of the diamond structures in Fig.2.

The entire diamond structure is embedded in a copper (or alumina) holder with the use of four individual diamond pieces of 100  $\mu\text{m}$  to provide mechanical alignment and robust conducting boundary compared to thin layer metallic deposition. Single piece growth of a similar polycrystalline diamond structure is also considered using the CVD process alone.

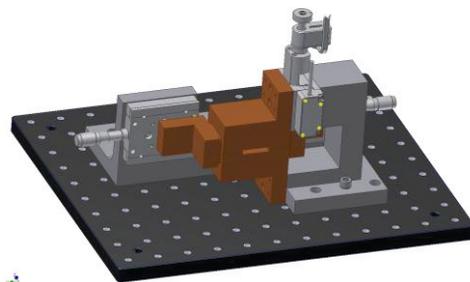


Figure 4: CAD drawing of the DLA structure and holder with a variable aperture of 50 – 950  $\mu\text{m}$ .

Currently we are designing the next generation of tunable DLA THz structures with adjustable aperture, Fig.4. Structures like this can be used as tunable energy chirp compensators for short sub-picoseconds beams or energy modulators for longer beams [9,13]. In this investigation, Raman spectroscopy has been used as a standard tool to identify the spectral width of the  $sp^3$  peak and the ratio of the  $sp^2$  to  $sp^3$  signals. The FWHM of the diamond peak from the Raman spectrum can be used as one measure of the diamond quality. The sharper the spectrum peak, the better the diamond crystal. Fig. 5 presents a typical spectrum measured from the diamond samples that are used for diamond-based DLA structures.

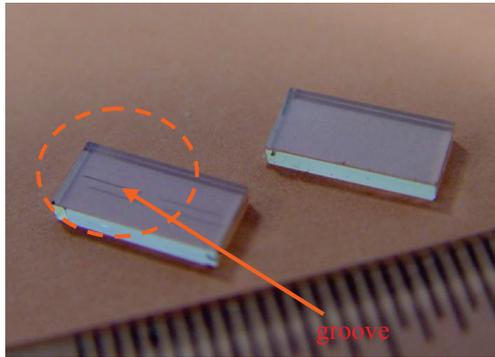


Figure 5: Field Enhancement groove machined in a planar diamond sample.

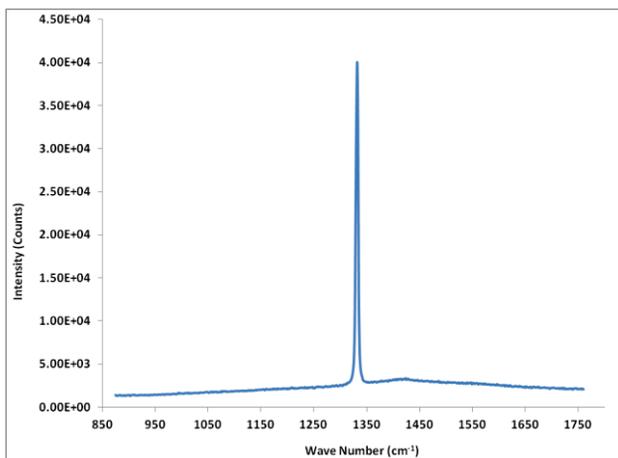


Figure 6: Raman spectrum of a diamond DLA sample.

## BEAM EXPERIMENTS WITH THE DIAMOND BASED DLA STRUCTURES

Recently, we have directly measured THz wakefield acceleration/deceleration in a diamond loaded dielectric accelerating structure. It should be noted especially that in this experiment carried out at the BNL Accelerator Test Facility (ATF) diamond was for the first time used as a loading material for a wakefield dielectric based

accelerating structure [9]. Fields produced by a leading (drive) beam were used to accelerate a trailing (witness) electron bunch, which followed the drive bunch at a variable distance. The energy gain of a witness bunch as a function of its separation from the drive bunch describes the time structure of the generated wakefield. By sweeping the separation between the drive beam and the witness beam and energy measurements of the witness beam a 0.25 THz frequency wakefield was directly sampled at the scale of about one wavelength [9,13].

## SUMMARY

The emphasis of this paper is to present progress on development and fabrication of new types of cylindrical and planar diamond waveguides to be used for high gradient dielectric accelerating structures. We reported the results from development of a cylindrical diamond DLA of GHz frequency range and wakefield tests of diamond-loaded rectangular accelerating structures at THz frequencies. We have directly measured THz wakefield acceleration/deceleration in a diamond loaded dielectric accelerating structure in an experiment where diamond was used for the first time in a wakefield dielectric based accelerating structure. In the 25 GHz frequency range, we achieved field levels on the order of 300 MV/m in the structure using the  $\sim 100$  nC, 15 MeV beam at the Argonne Wakefield Accelerator Facility. Single crystal diamond plates produced by chemical vapor deposition (CVD) were used in the structure. A surface analysis of the diamond has been performed before and after the beam test.

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