DEVELOPMENTS ON A DIAMOND- BASED CYLINDRICAL DIELECTRIC ACCELERATING STRUCTURE

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Abstract

Developments on a high gradient diamond-based cylindrical dielectric loaded accelerator (DLA) are presented. A diamond-loaded DLA can potentially sustain accelerating gradients far in excess of the limits experimentally observed for conventional metallic accelerating structures. The electrical and mechanical properties of diamond make it an ideal candidate material for use in dielectric accelerators: high RF breakdown level, extremely low dielectric losses and the highest available thermoconductive coefficient. We used the hot-filament Chemical Vapor Deposition (CVD) process to produce high quality 5-10 cm long cylindrical diamond layers. Our collaboration has also been developing a new method of CVD diamond surface preparation that reduces the secondary electron emission coefficient below unity. Special attention was paid to the numerical optimization of the coupling section, where the surface magnetic and electric fields were minimized relative to the accelerating gradient and within known metal surface breakdown limits.

INTRODUCTION

Dielectric Loaded Accelerator (DLA) 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 [1]. The aim of this paper is to present a diamond-based DLA that supports a sustained accelerating gradient larger than 600 MV/m, far in excess of the limits experimentally observed for conventional metallic accelerating structures. A planar diamond-based DLA structure was proposed in [2] and studied recently by Omega-P, Inc. [3]. The dielectric for this structure was to be made of diamond slabs fabricated using CVD (chemical vapor deposition) technology similar to that used for RF windows and currently available for planar geometries only. Meanwhile it is known that a cylindrical structure naturally has larger shunt impedance and a much higher efficiency than a planar structure due to its favorable geometry factor. In this paper, we discuss a new technology for the development of *cylindrical* diamond-based waveguides and the design, fabrication and high power testing of a *cylindrical diamond-based* DLA accelerating structure. The final goal is a record high accelerating gradient (~ 600 MV/m) demonstration of the structure at high power and with accelerated beam.

DIAMOND-BASED DLA STRUCTURE DEVELOPMENT

The method used for fabrication of the diamond tubes is based on a CVD (Chemical Vapor Deposition) process. CVD involves a gas-phase chemical reaction occurring above a solid surface, which causes deposition onto that surface. The gas mixture used in this technique is nothing more exotic than a gas that contains carbon (typically methane) in an excess of hydrogen atoms. The latter are generated as a result of the gas mixture being ionized either thermally or via electron impact. The activated gas molecules and hydrogen atoms then settle on a surface where the carbon atoms lock together to form a thin diamond coating. The coatings that result can range in thickness from nanometers to millimeters, depending upon which deposition process is used and for how long the deposition apparatus is run.

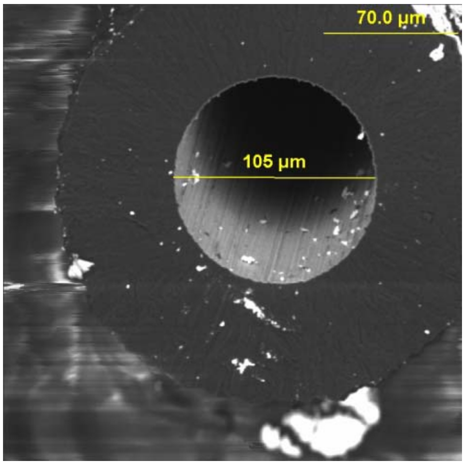

Figure 1: SEM cross-sectional surface images of a diamond tube deposited on a 105-µm diameter substrate. Note the 70 µm thickness of the tube along with the inner surface roughness of less than 1µm.

CVD permits the deposition of thin-film diamond coatings or the growth of thick diamond materials in different shapes. Diamond tubes are of interest for applications such as molecular filters, drilling tools, waveguides, hypodermic needles and others [4]. The geometry required may be achieved by using a cylindrical substrate during the CVD process, with subsequent etching of the substrate. Rather than a planar surface, Ti or W metal rods are used as hot-filament CVD substrates.

When the diamond deposition process is completed and the tube wall thickness reaches the required waveguide dimensions, the metal rods will be etched off to form self-supporting diamond tubes.

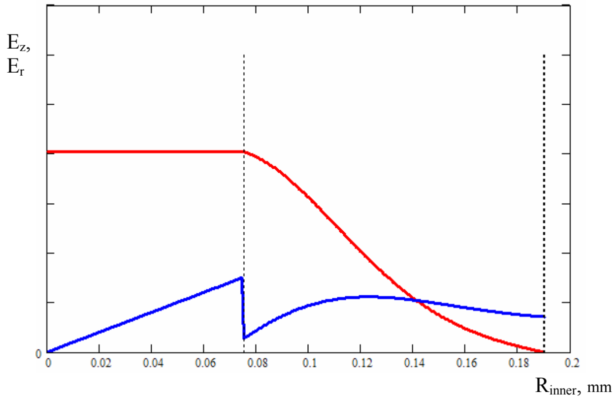

Figure 2: Longitudinal (red) and transverse (blue) electric field profiles normalized to the accelerating gradient E_{accel} for a structure of inner diameter 2a = 1.5 mm, outer diameter 2b = 3.79 mm, diamond thickness 1.15 mm, and no gap between the dielectric and copper wall.

The internal diameter of the tube depends on the diameter of the substrate and the wall thickness is determined by the deposition time. It should be noticed that the surface roughness is less than few micrometers (Fig. 1), critically important if the tube is used as part of a DLA structure.

The nature of the growth of the diamond tubes depends strongly on: (i) the 'incubation' (the complex mechanisms of the carbon saturation on the substrate surface prior to the onset of a high diamond nucleation rate), and (ii) the growth of diamond on diamond after the first diamond layer is formed. Typical values for the rate of diamond overgrowth on diamond and the 'incubation' time on tungsten are approximately 7.8 µm/hour and more than 3 h, respectively, under similar process conditions [4].

Fig. 1 presents a SEM cross-sectional surface image of a diamond waveguide developed for an upcoming SLAC/UCLA high gradient (> 1GV/m) DLA structure demonstration experiment [10].

Numerical Simulations of a Diamond-Based Cylindrical DLA

A DLA structure, unlike a conventional metallic one, admits the unique possibility of sustaining extremely high gradients by using a diamond-based material as the dielectric loading of the waveguide structure. Field analysis for diamond-based DLA structures can be carried out analytically. The operating mode for the cylindrical DLA structure is TM_{01}. Parameters of the diamond-based DLA structures with the 1.5 mm and 3 mm apertures are presented in Table 1. The structure operates in the TM_{01} mode in the Ka band frequency range where its axial wave number corresponds to a phase velocity of c; the diamond has dielectric constant of 5.7 and loss tangent $\tan\delta = 5 \times 10^{-5}$. Loss tangent values for CVD diamond bulk material are published in a variety of sources. The best samples of the CVD diamond developed for gyrotron windows and other high frequency applications have loss tangent values in the range of $(1\text{-}10)\times10^{-4}$ over the 40-140 GHz frequency band. We used an average value of 5×10^{-5} in our simulations.

The radial field profiles normalized to the accelerating gradient for the 34 GHz diamond-based structure are presented in Fig. 2. The accelerating gradient is equal to the maximum E_z field magnitude on the inner dielectric (diamond) surface. The transverse E_r /E_{accel} ratio on this surface does not exceed 0.37 at the dielectric-vacuum- and 0.17 at the dielectric-metal interface. The structure is assumed to have no vacuum gap between the diamond surface and the copper wall of the accelerator. It was shown previously that for the DLA structures direct contact of the dielectric tube with the conducting walls results in increased surface currents and relatively high Ohmic losses in the walls [3]. Note that vacuum gaps can be naturally introduced between the dielectric loading and the side conducting walls to reduce the surface currents and wall losses; as a result, the shunt impedance of the structure can be significantly increased.

Table 1: Diamond-based cylindrical DLA structure parameters for the case of a 2 mm vacuum gap between the outer diamond surface and the copper wall. Note the high shunt impedance of 262 MΩ/m for the vacuum gap case. The surface field ratio $E_{metal}/E_{accelerating}$ > 0.49 for a 1.5 mm beam channel aperture.

Inner Diameter	2000 µm vacuum gap	
	1.5 mm	**3 mm**
R_{outer}, cm	0.19	0.24
P_{attn}, dB/m	-0.22	-0.24
r_s, MΩ/m	262	132
$E_{z.diel}/E_{z.accel}$	1	1
$E_{r.diel}/E_{z.accel}$	0.9	0.9
$E_{r.metal}/E_{z.accel}$	0.49	0.79

Table 1 presents the accelerating structure parameters for a Ka-band diamond-based DLA with a vacuum gap of 2 mm. From Table 1, the shunt impedance R= 262 MΩ/m for an aperture of 1.5 mm. Simulations showed that the maximum shunt impedance Rmax increases with 1/Rc along with the accelerating gradient. Note that for the rectangular DLA structure the larger aperture decreases the shunt impedance [3], another advantage of the cylindrical design presented in this project. The critical electric field ratio of ~0.5 implies that the maximum possible gradient is 600-700 MV/m. At the same time, the power attenuation decreased dramatically to 0.22 dB/m in favor of a high shunt impedance. It should be noted that the vacuum gaps located between the diamond and conducting wall surfaces increase the group velocity of the structure. The final diamond-based DLA parameters should be chosen as a result of a trade-off between high gradient and high shunt impedance, and on the other hand, the power attenuation and group velocity required.

In either case, the accelerating gradients available with the diamond-based DLA structure are evidently well in excess of those for iris-loaded all-metal accelerating structures [5]. For an externally powered DLA structure accelerating gradient limitations are primarily defined by the coupler electric and magnetic field enhancements that will be discussed in [9].

CVD Diamond Surface and Multipacting Performance

During the last decade, much attention was focused on studying the fundamental properties and applications of CVD diamond. CVD diamond is known in the accelerator community mostly as a material for dielectric-based cold cathodes and photocathodes in high-power electronics, in radiation hard detectors, and for stripper foils. It is also a promising semiconductor material for novel electronic applications [9].

It is known that hydrogenated CVD diamond films possess a strong NEA with a high coefficient of secondary electron emission (>60). It is important to note that a high SEE coefficient has been demonstrated with a hydrogenated diamond surface; special actions have to be performed like adding an additional surface coating (CsI) for maintaining a high secondary electron yield for cathode and photocathode-like device applications [9].

At the same time, dehydrogenated or oxidized diamond surfaces show a positive electron affinity and demonstrate SEE coefficients ~1. Consequently this type of surface preparation can be used for a dielectric loading material for high gradient DLA structures with reduced or suppressed multipacting performance [6-8]. Initially diamond-like materials were even considered as a material for the suppression of secondary electron emissions [8]. The SEE coefficient was monitored after electron beam exposure and annealing and found to sharply decrease from the initial value of about 70 to about 1 [6]. The removal of the hydrogen, either by an acid-cleaning process or by thermal desorption, resulted in a drastic reduction in the yield [7].

Diamond surfaces may be oxidized in a number of ways (e.g. oxidizing acid or oxygen plasma treatments), resulting in PEA [7]. In conclusion, bulk and films of CVD diamond can be fabricated with a surface having a secondary electron emission yield (~1). This requires that hydrogen should be desorbed from the diamond surface or the surface should be oxidized. Nitrogen and other CVD diamond dopants should be considered as well [7].

SUMMARY

A new type of cylindrical Dielectric Loaded Accelerating (DLA) structure based on a diamond waveguide has been presented. Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material will allow high accelerating gradients up to 0.5-1.0 GV/m as long as the diamond surface can sustain a 1-2GV/m breakdown rf field. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity and an extremely low loss tangent (<10-4) in the Ka-W frequency bands. Multipacting performance of the CVD diamond can be dramatically suppressed by diamond surface dehydrogenation. For a cylindrical diamond-based DLA structure, the electric fields at the dielectric surface would be less than 1 GV/m for an acceleration gradient exceeding 600-700 MV/m. The diamond-loaded structure will have a shunt impedance of 150-200 MΩ/m. Our preliminary coupling section model showed that 60-80% field ratios can be achieved to support a > 600 MV/m accelerating gradient. The feasibility of making DLA structures high gradient capable is of considerable interest for the development of the future high gradient accelerators, and multi-TeV linear collider in particular.

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