DEVELOPMENT OF A GHZ/THZ SOURCE BASED ON A DIAMOND STRUCTURE*

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Abstract

There has been considerable progress in using microfabrication techniques to produce experimental rf sources. These devices have for the most part been based on micromachined copper surfaces or silicon wafers. We are developing GHz/THz diamond wakefield structures produced using Chemical Vapor Deposition (CVD) technology. The electrical and mechanical properties of diamond make it an ideal candidate material for use in dielectric rf structures: high breakdown voltage (~600 MV/m), extremely low dielectric losses and the highest thermoconductive coefficient available for removing waste heat from the device. These structures are based on cylindrical diamond dielectric tubes that are manufactured via a relatively simple and inexpensive chemical vapor deposition (CVD) process, plasma assisted CVD. Use of the CVD process is a much simpler method to achieve high quality rf microcavities compared to other microfabrication techniques. We are designing a number of diamond rf structures with fundamental TM_{01} frequencies in the 0.1-1 THz range. Numerical simulations of planned experiments with these structures will be reported.

INTRODUCTION

The principal goal of this project is to develop a diamond-based DLA to allow a sustained accelerating gradient larger than 600 MV/m, far in excess of the limits experimentally observed for conventional metallic accelerating structures. We have developed devices operating in a number of frequency bands and manufactured using different technologies appropriate to the specific physical dimensions of the structure.

The methods we used for fabrication of the diamond tubes are based on CVD (Chemical Vapor Deposition) processes. Our choice of CVD diamond as a loading material will allow demonstration of accelerating gradients as high as 0.4-0.6 GV/m as long as the diamond surface can sustain as expected a 1-2 GV/m breakdown rf field [1,2,7,8]. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity [5] and extremely low loss tangent ($<10^{-4}$) at Ka-W frequency bands [6,8]. Multipacting in diamond is a strong function of surface termination and may be suppressed by diamond surface dehydrogenation [2,7-8].

Our initial work was based on 100 μm 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 to deposit a diamond layer on a cylindrical metal armature [1,2]. When the diamond deposition process is completed and the tube wall thickness reaches the required waveguide dimensions, the metal rods are etched out to form self-supporting diamond tubes.

For the larger structures required for Ka band (34 GHz) and longer wavelength applications, the use of microwave plasma-enhanced CVD (PECVD) was determined to have a greater likelihood of success based on its larger rate of diamond deposition and the ability to control surface temperatures on the substrate during deposition. With CTS, Inc., we have obtained promising results using a water cooled armature to produce a 5 mm ID free standing diamond tube. We have also developed and demonstrated a completely new process for producing azimuthally segmented cylindrical structures created by PECVD processing of appropriately machined planar substrates [8].

Figure 1. Photograph of CVD diamond tube developed by our collaboration, top view. Tube parameters are: 5 mm inner diameter, 2.5 cm length and ~ 500 μm thick.

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 [3]. A planar diamond-based DLA structure was proposed [4,5] and studied recently by Omega-P, Inc. [5]. The dielectric loading of this structure was to be made of diamond slabs fabricated using the CVD (chemical vapor deposition) technology similar to that used for RF windows and currently available only for planar geometries. Meanwhile it is known that a cylindrical structure naturally has a larger shunt impedance and a much higher efficiency than a planar structure due to its favorable geometry factor [1,2] . We present here the first cylindrical 5 mm ID free standing CVD diamond loading in Fig. 1. This demonstrates the feasibility of CVD diamond-based cylindrical Ka-band DLA structures.

DIAMOND CYLINDRICAL WAVEGUIDE FABRICATION

PECVD Diamond Tube Fabrication.

In this section we describe the technology and results of the diamond accelerator structure manufacturing experiments. The 5 mm inner diameter, 2.5 cm long and 500 μm thick diamond tube has been fabricated and characterized with SEM, micro-Raman and micro-photoluminescence spectrum analysis. Fig.1 shows the finished free standing diamond tube. This tube represents considerable progress in diamond based accelerator development. Fig. 2 presents an optical image of the newly developed cylindrical diamond showing the improved shape and diamond quality. The new free standing tube developed in 2009 is well shaped and has a much smoother surface than those from the first attempts in the 2006 project [7,8].

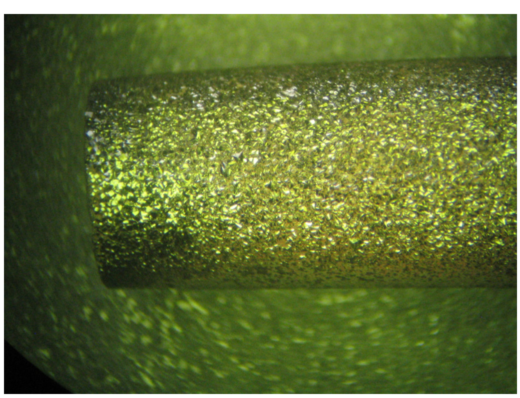

Figure 2. Photographs of the outer surface of the 5 mm ID diamond tube. Light reflects off the naturally smooth individual facets of diamond crystals comprising the polycrystalline aggregate. Large crystals generally exhibit better properties.

The standard method of making high grade diamond relies on this idea: diamond is grown thick (usually 1.0-1.5mm thick), the substrate is removed (usually etched off) and the nucleation side is then removed (usually lapped or polished) to obtain the final thickness.

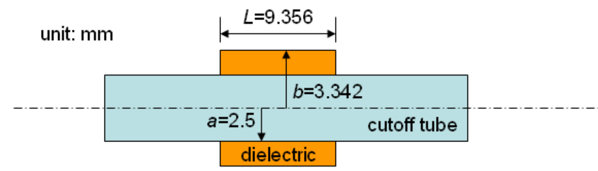

Figure 3. . The 35.1GHz cavity based on a diamond-loaded waveguide.

This is because typically the nucleation side is of poorer quality than the growth side due to a higher density of grain boundaries. Fig.1 and Fig.2 show the diamond tube after removal of the substrate and laser trimming of the ends of the tube. Micro-Raman and micro-photoluminescence spectra were measured at 3 spots on the tube using 488 nm laser excitation. All three micro-Raman spectra show a distinct diamond zone center phonon band at 1332 cm^{-1} shift from the laser superimposed on a broad photoluminescence background. The sharpness of the phonon peak indicates reasonably crystalline diamond material (polycrystalline in this case).

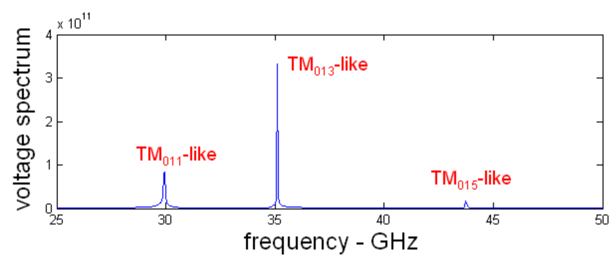

Figure 4. Voltage spectrum of the signal generated with the SW cavity shown in Fig. 3.

Numerical Simulations of a Diamond-Based Cylindrical DLA

In order to investigate the potential of diamond-loaded waveguides for future high power, high gradient particle acceleration, a 35 GHz standing-wave structure has been designed for beam tests at the Argonne Wakefield Accelerator (AWA). The AWA beamline consists of an electron gun and a linac, both operating at 1.3GHz, leading to a bunch frequency also at 1.3GHz. The electron gun is able to deliver 1-100nC charge per bunch with an r.m.s. bunch length of σz = 1.5-2.5mm. The beam energy is ~8MeV upon exiting the gun and is accelerated to ~15MeV by the linac [9].

First the transverse dimensions of the diamond-loaded waveguide are adjusted so that the synchronous frequency of the TM_{01} mode is 35.1GHz, the 27th harmonic of the operating frequency of the AWA gun and linac. The waveguide described in Table 1 is then used to form a standing-wave cavity, with two cutoff tubes at both ends whose dimensions are the same as that of the beam channel in the diamond-loaded waveguide.

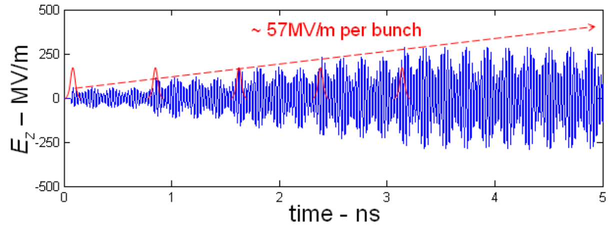

Figure 5. Longitudinal E-field excited by a train of 5 bunches repeated at 1.3GHz.

The dimensions of the 35.1GHz cavity are shown in Fig. 3, where it can be seen that the length of the dielectric tube is 9.356mm. CST MAFIA was used to simulate the gradient excited inside this structure, by a single Gaussian bunch with an r.m.s bunch length of 1.5mm and charge of 50nC. Losses are ignored in the calculation for simplicity. An E_z probe for monitoring the longitudinal field is placed at the center of this cavity (r = 0 and z = 0). Fig.4 shows the voltage spectrum, where it can be seen that the TM_{011}-like and TM_{015}-like modes also possess significant power. To emulate the effect of excitation of a bunch train, the signal is repeated at the bunch frequency 1.3GHz and then summed to obtain the total E_z signal. Fig. 5 shows the total E_z signal excited by a train consists of 5 bunches, and when more bunches are added the envelope of the signal will keep growing due to the large Q. It can be seen that the contribution of beam to the E_z signal is approximately 57MV/m per bunch, close to the single bunch value 60MV/m. The total gradient after 3 ns exceeds 250 MV/m.

Table 1. 35.1 GHz standing wave structure parameters.

RF frequency	f_0	35.1GHz
Beam channel height	$2a$	4.32mm
Dielectric-loaded waveguide height	$2b$	5.72mm
Dielectric-loaded waveguide width	w	10mm
Relative permittivity of the dielectric	ε_r	5.7
Group velocity of RF mode	v_g	0.363c
Loss tangent of dielectric	σ_d	1×10-4
Wall quality factor (metallic loss only)	Q_w	3448
Total quality factor (metallic and dielectric losses)	Q	3011
"r over Q" per unit length	$[r/Q]$	9.80kΩ/m
Shunt impedance per unit length	r_{sh}	29.5MΩ/m

SUMMARY

A new type of cylindrical Dielectric Loaded Accelerating (DLA) structure based on a diamond waveguide has been presented. Critical technologies relevant to the demonstration of diamond accelerating structures have been demonstrated: production of 34-35 GHz CVD diamond tubes with inner diameter of 5 mm, wall thickness of ~ 500 um, dielectric constant of 5.7, loss tangent tanδ ~ 1×10^{-4}; characterization of diamond properties and rf measurements of CVD diamond dielectric parameters; micro-Raman and micro-photoluminescence spectra using 488 nm laser excitation have been studied; numerical simulations of wakefields in cylindrical diamond-based DLA structures to be experimentally tested at the AWA 15 MeV high brightness beam.

Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material is anticipated to allow demonstration of high accelerating gradients up to 0.6 GV/m. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity and extremely low loss tangent ($<10^{-4}$) at Ka-W frequency bands. Multipacting performance of the CVD diamond can be dramatically suppressed by diamond surface dehydrogenation.

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REFERENCES

[1] A. Kanareykin. P. Schoessow, M. Conde et al. AIP Conference Proceedings, V. 877, p. 320, 2006.
[2] A.Kanareykin, P.Schoessow, M.Conde et al. Proceedings of EPAC2006, p. 2460, 2006.
[3] W. Gai, P. Schoessow, B. Cole et al. Phys. Rev. Lett. 61, 2756 (1988).
[4] M. E. Hill, et al., SLAC-PUB-8666. D.Whittum. AIP Conf. Proc. 1-56396-889-4/
[5] C.Wang, V.P.Yakovlev and J.L.Hirshfield. Proceedings Particle Accelerator Conference PAC-2005, pp.1282-1284, 2005.
[6] V. F. Matveichuck, Measurement Techniques 42(6) p.603, 1999.
[7] P. Schoessow, A. Kanareykin, and R. Gat. AIP Conf. Proc., NY, American Institute of Physics, v. 1086, pp.398-403, 2008.
[8] A. Kanareykin et al. Proceedings of PAC2007, Albuquerque, NM, pp. 3163-3165, 2007.
[9] M.E. Conde et al. Proceedings EPAC, 2006, Genova, pp. 2835-2837.