ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT037

CERAMICS EVALUATION FOR MW-POWER COAXIAL WINDOWS, OPERATING IN UHF FREQUENCY RANGE*

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Abstract

Modern accelerator facilities require reliable high-power RF components. The RF vacuum window is a critical part of the waveguide couplers to the accelerating cavities. It is the point where the RF feed crosses the vacuum boundary and thus forms part of the confinement barrier. RF windows must be designed to have low power dissipation inside their ceramic, be resistant to mechanical stresses, and free of discharges. In this paper, we report on the evaluation of three different ceramic candidates for high power RF windows. These materials have low loss tangents, low secondary electron yield (SEY), and large thermal expansion coefficients. The acquired materials were inspected, coated, and measured to select the optimal set.

INTRODUCTION

Conventional RF vacuum windows are made from ceramics, such as BeO or 96-99% Al_2O_3, or plastics such as Rexolite that are then brazed or otherwise joined to a pillbox cavity [1]. The use of ceramics presents several major challenges and issues that limit the performance of the existing RF windows. First, the fabrication and machining of large ceramics discs can be challenging. For example, at 400 MHz frequency, the size of waveguide is 11.5×23 inches, which means that discs of >13'' must be fabricated. Size also increases ceramic-to-metal brazing process complexity due to temperature differentials and residual stress.

Another set of problem is related to operational conditions of the RF windows. First, since high-power accelerators for accelerator facilities require transmission of multi-MW RF power at ~10% duty-factors, the transmitted power level reach hundreds of kW and dielectric losses present a serious issue [2]. For example, the losses at this frequency are defined by the loss factor ($\varepsilon \cdot \tan\delta$), which is typically $>1-2\cdot10^{-3}$. This about an order of magnitude higher than novel low-loss dielectrics [3,4]. Besides net losses in the dielectric, its thermal conductivity should be considered. Materials with low thermal conductivity, such as rexolite, suffer from internal heating and thermo-mechanical stresses gradients that can lead to stress fractures. Finally, the electric discharges due to static charge build-up or multipactor discharges play a great role in the reliability of RF windows [5,6]. Coatings such as titanium nitride are needed to suppress multipacting, requiring careful process control to uniform thickness over a large area.

In response to this problem, we surveyed several readily available dielectrics, such as high-purity alumina, sapphire, aluminum nitride, Si3N4, sapphal, MgTi, and others, and identified the optimal candidates for high-power RF windows.

MATERIAL SELECTION CRITERIA

The critical material properties of the dielectric include RF, thermal, and mechanical considerations, along with manufacturing related requirements such as commercial availability, machinability, capability for brazing, and SEY reducing coating [7]. The important RF properties include a low loss tangent (tan δ) to avoid high-power dissipation in the window, a low secondary electron emission coefficient to suppress multipacting, a low dielectric constant (ε) to simplify impedance matching and a high dielectric strength to withstand breakdown. High thermal conductivity (κ) is desirable to conduct the dissipated power through the braze joint into the actively cooled metal body. A meaningful figure of merit of a ceramic is the ratio of thermal conductivity to loss tangent times permittivity, $FOM = \kappa/(\varepsilon^* \tan\delta)$. This FOM captures that for every watt of loss in the ceramic (tan δ), the materials thermal conductivity (k) must allow that power to be removed by the temperature differential caused by the active cooling. Note that a high FOM is desirable.

Mechanical strength capable of withstanding differential pressure associated with the vacuum barrier is also required. High fracture toughness is desirable, as this makes the material more robust against fracture from fabrication, operation, or cyclic loading (vacuum, thermal, transport). Another important property of the dielectric is the capability for brazing, either by metallization or the use of active braze alloys. Materials with low outgassing characteristics are important, implying that the material is easily cleaned and vacuum conditioned. Toxicity of the dielectric is also a concern, causing high-performing materials such as beryllium oxide to be phased out.

These parameters must be considered within a practical engineering context. First and foremost: the dielectrics must be commercially available in large sizes with limited development and realistic lead times. Procuring and qualifying expensive capital equipment (presses, furnaces, etc.) to fabricate parts at scale should not be the objective of a RF window assembly manufacturer and is best left to organization with proven ceramics expertise. Additional issues such as variability in material properties, both within the part and part-to-part, impact the design safety margins. The capability to accurately shape and finish the ceramic

* This work was supported by the U.S. Department of Energy, Office of Basic Energy Science, under SBIR grant DE- SC0021552
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to dimension is important for fitment within the metallic assembly, as well as the performance of the SEY coating. Cost is always a significant consideration, precluding exotic materials like diamond. In other words, small-scale, lab-quality ceramic coupons with exceptional RF properties are of little practical use if they cannot meet the commercial mass-production requirements above.

Table 1: Comparison of the Main Properties of Window Dielectric Candidates.

Material	tanδ ·10^{-4}	ε	ε·tanδ ·10^{-4}	k, W/m/K	k/(ε· tanδ)
Rexolite	4.25	2.53	1.07	0.146	136.4
Al2O3-97.6%	2.1	9.52	2	26.8	13.4k
Al2O3-<99%	1	9.58	0.96	29.3	30.5k
AlN - ST-100	50	8.7	43.5	90	2070
AlN - ST-200	35	8.45	29.6	200	6750

A comparison of various dielectric materials used for windows, including polymer-based Rexolite, is shown in Table 1. From our FOM, we see that high purity alumina (>99%) has the best combination of heat transport and RF properties. In contrast, the exceptional thermal conductivity of Sienna Technologies ST-200 AlN [8] is negated by its high loss tangent, giving it a poor FOM in comparison to other materials.

COUPON INSPECTION

Based on our research, costs, lead time, and conversations with leading researchers, we down selected vendors capable of providing ultra-high purity alumina. These materials included AL995 from Morgan Ceramics (formerly Wesgo) [9], RF Pure AD998 from Coorstek [10] and AO479U from Kyocera [11,12]. From the FOM defined above, these materials are nominally identical, as difference in values can be attributed to variations in measurement setup.

Four coupons of each of the three selected materials were purchased from their respective manufacturers. The coupons were designed to fit into a standard 1-5/8" EIA coaxial transmission line and dimensional tolerances were chosen to balance cost and lead time against maintaining key features for multipactor suppression coating representative of a full-scale window, including surface roughness and flatness/parallelism. All coupons were mechanically inspected using calibrated micrometers, height gage, and surface profilometer (see Table 2). Since dimensional tolerances were well within each of the manufacturer's capabilities, coupons were evaluated for consistency and craftsmanship.

Mean surface roughness was measured with a 10 µm, 90° stylus tip with the following collection parameters: 30 µm gaussian filter, 0.8 mm sampling length, 0.5 mm/s scan speed, and 2.4mm scan length. Data was taken for each face in both radial and circumferential directions to quantify the final polishing anisotropy produced during fabrication. However, no significant difference between sample orientations was apparent in the data. These data identified AO479U samples with the highest level of dimensional consistency.

Table 2: Coupon Mechanical Inspection Data

Material	AO479U	AL995	AD998
Diameter STD, µm	14	15	45
Thickness STD, µm	0.8−1.9	3.4−5.3	0.6−4.5
Surface finish, µm			
Radial	11.6±2.1	38.7±9.8	22.8±6.5
Circumferential	10.7±3.3	36.3±6.2	23.5±7.5

Visual inspection with a stereo microscope and high magnification Keyence VHX 6000 digital microscope was performed. Though all coupons were of acceptable quality, this detailed visual inspection revealed some differences in fabrication approach and handling practices. The faces on Morgan coupons had a ground finish while AD998 and AO479U appear to have taken the additional step of lapping. The extra processing was reflected by the surface roughness measurements. AL995coupons also showed minor evidence of contamination with metallic residue on the outer diameter. AO479U coupons showed no visible defects or contamination and were remarkably consistent in visual appearance. Images of the coupons are shown in Fig. 1.

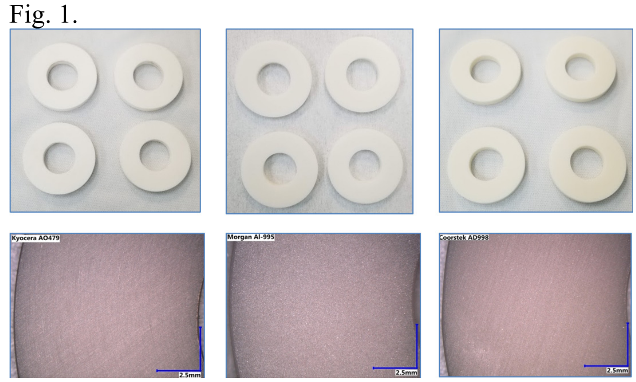

Figure 1: Uncoated coupons of AO479U (left), AL995 (middle) and AD998 (right).

RF MEASUREMENTS

The next step was to validate the low-level RF performance, including measurements of dielectric constant and loss tangent. We built a test stand consisting of a short coaxial transmission line loaded with coupons of the same material. The measurement procedure consisted of taking high precision reads of complex S_{11} and S_{21} across a 100 MHz − 1 GHz frequency range with the following configurations: empty transmission line and when loaded with a set of 2, 4 and 6 coupons. Then the loss tangent and dielectric constant are extracted from the measured power balance and the added phase delay. The results are listed in Table 2. Achieved measurement precision allows to state

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that the material's properties are within their specifications, except for Rexolite that showed higher loss factor.

Table 2: RF Measurements Results

Material	ε_{data}	ε_{meas}	$\tan\delta_{data} \cdot 10^{-4}$	$\tan\delta_{meas} \cdot 10^{-4}$
Rexolite	2.53	2.4−2.6	2	3-5
AO479U	9.65	9.5−9.8	0.2	<1
AL995	9.5	9.4−9.6	5	<1
AD998	9.8	9.7−10	<1	<1

SECONDARY EMISSION YIELD

Another concern for RF windows is the multipactor discharge. One of the most efficient ways to ensure its suppression is to reduce the SEY of the ceramics. Titanium nitride coatings (TiN) are widely used in industry because of their outstanding hardness and strength, anticorrosion properties, and high temperature stability. Therefore, alumina coupons from each vendor were coated with TiN with 10 nm layer thickness using reactive RF magnetron sputtering using facilities located at SLAC.

Sputtering is a physical vapor deposition (PVD) process involving a gaseous plasma which is generated and confined around the material to be deposited, commonly referred to as the "target." The target surface is eroded by high-energy ions within the plasma which then travel through the vacuum and deposit onto a substrate, forming a thin film. RF magnetron (13.56 MHz) sputtering was preferred over DC sputtering because of availability and ease of setup. Reactive sputtering refers to a process which uses reactive gases such as oxygen or nitrogen as the plasma medium. In the case of TiN PVD, a titanium target is used with an Ar/N_2 process gas.

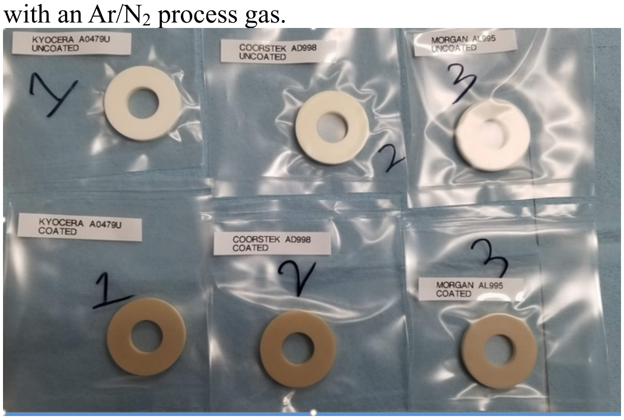

Figure 2: Coated and uncoated alumina coupons immediately after TiN PVD.

As shown in Fig.2, the TiN coating changes the coloration of all the ceramic coupons. The surface of each coupon was inspected under an SEM at Los Alamos National Lab (LANL) (Fig.3). To deposit a TiN coating with a specific thickness, best practice dictates that a test coating should first be deposited then the thickness is checked using offline measurements such as Rutherford Backscattering. To coat the part with the desired thickness, the time of exposure is then adjusted according to the initial calibration run assuming that the PVD conditions are identical. The resulting thickness is estimated slightly higher, and the future work will include measurement.

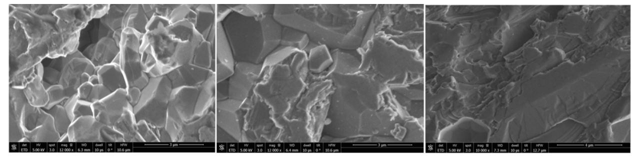

Figure 3: AO479U (left), AD998 (center) and AL995 (right) samples under SEM examination with TiN coating.

Researchers at LANL measured SEY on the TiN-coated coupons. Note that these coupons were simultaneously coated in the same deposition campaign, therefore differences in SEY can be attributed to the alumina dielectric itself, which can include variables such as contamination, surface finish, and microstructure.

The SEY measurement principle consists of recording the incident and reflected electron beam current using different incident beam energy and sample bias voltages [13]. Typically, this measurement is performed in a scanning electron microscope (SEM) which includes additional features to measure the incident electron beam current (i.e. Faraday cup), detect the reflected beam current, and bias the sample surface.

The SEY measurement results are presented in Fig. 4. From these results, the TiN coating on the Morgan coupon performed the best, with SEY <= 1 for all incident beam energies. The differences in SEY performance can be attributed to microscopic differences in the ceramic, such as particle size and morphology, as well as difference in surface finish.

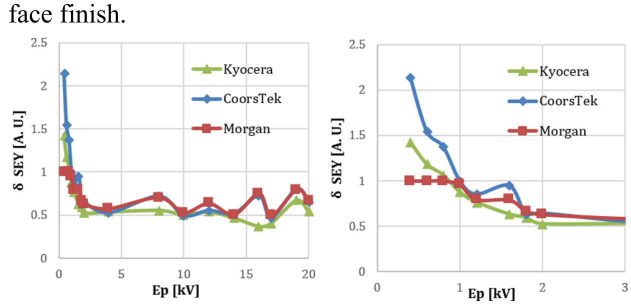

Figure 4: SEY measurements of TiN coated alumina coupons performed at LANL.

CONCLUSION

Several ceramic materials were considered for applications in high-power RF windows in terms of loss factor, thermal conductivity, fabrication feasibility, secondary-emission yield (SEY), reliability, availability, and cost. Based on these criteria, we opted for a high-pure alumina and ordered three samples from different vendors: AL995 from Morgan Ceramic, AD998 from Coorstek and AO479U from Kyocera. These samples were received, inspected, TiN-coated and tested for mechanical, RF properties and SEY. Based on this evaluation, we have concluded that AO479U material is the optimal material candidate in terms of surface finish, RF properties, and provides a reasonable SEY after TiN coating.

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REFERENCES

[1] K.A. Cummings, S.H. Risbud, “Dielectric materials for window applications”, *J. Phys. Chem. Solids* vol. 61, no. 4, p.551-560, 2000.

[2] Y. Kang, “Experiences and Developments with RF Power Couplers in ORNL SNS”, presented at WWFPC #5, June 25 - 26, 2019.

[3] H.J. Jo, J.S. Kim, E.S. Kim, “Microwave dielectric properties of MgTiO3-based ceramics”, *Ceram. Int,* vol. 41, no. 1, p. 530-536, 2015.

[4] D. Satoh *et al.,* “Power efficiency enhancement of dielectric assist accelerating structure”, *Nucl. Instrum. Methods Phys. Res. Sect. B,* vol. 459, pp. 148–152, 2019.

[5] J. Rodneym M. Vaughan, “Multipactor”, *IEEE Trans. Electron Devices,* vol. 35, No 7, July 1988.

[6] S. Michizono, "Secondary Electron Emission from Alumina RF Windows," 2006 presented at International Symposium on Discharges and Electrical Insulation in Vacuum, Matsue, 2006, pp. 91-96.

[7] S.V. Kutsaev, M.P. Kelly, P.N. Ostroumov, “Design of RF power coupler for superconducting cavities”, *J. Instrum.* Vol. 7, p.11004, 2012.

[8] https://siennatech.com/wp-content/uploads/2018/03/ST-200-AlN.pdf

[9] https://www.morgantechnicalceramics.com/media/2297/al995-version-2.pdf

[10] https://datasheets.globalspec.com/ds/1572/CoorsTek

[11] https://global.kyocera.com/prdct/semicon/material

[12] Y. Yamamoto, S. Michizono, “Ceramic Study on RF Windows for Power Coupler, Waveguide, and Klystron in Particle Accelerator” in *Proc. 19th Int. Conf. on RF Superconductivity SRF2019,* Dresden, Germany, 2019, pp.255-259.

[13] V. Baglin, *et al.,* “The secondary electron yield of technical materials and its variation with surface treatments”. LHC Projec Report 433, 2000.