Thermal & Structural Study of various Materials for High Power 170 GHz RF Window Characterization

Monika Sharma[1], Surbhi Adya[1,*], Rajendra Kumar Verma[1,2], Shivendra Maurya[1,2], V.V.P Singh[1]

[1]*Council of Scientific and Industrial Research - Central Electronics Engineering Research Institute (CSIR-CEERI), Pilani, Rajasthan, India.*

[2]*Academy of Scientific and Innovation Research (AcSIR), Taramani, Chennai, Tamil Nadu, India*

[*]surbhiadya@gmail.com

***Abstract*— This paper presents thermal and structural simulation results of various nitrides namely silicon nitride (Si_3N_4), Boron Nitride (BN) and Aluminium Nitride (AlN), to compare these materials with CVD diamond and Beryllia as a single-disc edge-cooled RF window for transmitting 1MW CW power at 170 GHz. In this study the suitability of materials has been investigated and analyzed by thermal and structural simulation for Gaussian power distribution using ANSYS Multi-physics. It is well known that CVD diamond is the best material for high power window application and same is found in this investigation. As an alternate it is also found that thermally Beryllia and structurally Silicon Nitride is the next best material, to be used for 1MW 170GHz Gaussian beam transmission in long pulse mode.**

Keywords—CVD Diamond, Nitrides, Beryllia, RF Window, ANSYS Multi-physics, Thermal Simulation, Structural Simulation, High power, Gaussian beam transmission.

I. INTRODUCTION

High power microwave vacuum electron devices like Gyrotron, other gyro-devices and electron cyclotron resonance heating systems require RF windows, which act as a pressure barrier being essentially transparent to intense millimeter wave radiation. These windows should be capable of handling MW level CW power with Gaussian distribution at frequencies of 100GHz and beyond.

CW power levels of 250kW at 140GHz have been realized [1]. Using oxides, mainly, Sapphire as material and liquid nitrogen as coolant, cryogenically cooled windows have been found to reach up to maximum power level of about 500kW CW at or around 150GHz [2]. Windows made of Beryllia have been used successfully for over 250kW at X-band [3]. Multi-layered windows has been used for broadband applications [4-5]. Other schemes of broad banding for gyro-devices have also been employed [6]. However, for simplicity of use the single disc edge-cooled windows are preferred. It is already a known fact that dielectric heating increases proportionately with frequency, and CVD diamond is the most favorable material for transmitting power more than 1 MW CW at frequencies 100GHz and beyond [7-9]. Despite of the numerous advantages of diamond it is very costly and hence an alternate material is required. So thermal & structural simulation and theoretical investigation and analysis for Gaussian power distribution using ANSYS Multi-physics has been carried out on nitrides; Si_3N_4, BN and AlN to find how these materials could be compared with CVD Diamond and Beryllia as single-disc edge-cooled window for transmitting 1MW CW power at 170 GHz. Single disc BN windows have been reported in use for 110 GHz Gyrotron for few seconds [9-11]. Si_3N_4 composite has been investigated earlier for its use in industrial Gyrotrons [12].

II. DESIGN

The two types of simulation and analysis of the RF window are discussed below:

A. *Thermal Analysis*

The thermal simulation has been done to compute the temperature distribution in the ceramic discs caused by absorbed Gaussian power due to dielectric loss and distributed on the disc as given in equation (1) [7].

$$\mathrm{P_a(r)} = \frac{2}{\pi \mathrm{w}^2} \mathrm{e}^{-2\left(\frac{\mathrm{r}^2}{\mathrm{w}^2}\right)} * \mathrm{P} * \mathrm{A_d} \qquad (1)$$

where $\mathrm{P_a(r)}$ is absorbed power density at position r in the disc, $\mathrm{A_d}$ is absorption coefficient. The absorption coefficient is calculated using equation (2).

$$A_d = \frac{2\pi * f * t * tan\delta * \epsilon_r}{c} \qquad (2)$$

where f, t, $tan\delta$, ϵ_r and c are frequency, disc thickness, loss tangent of dielectric material, dielectric constant, and velocity of light respectively.

B. *Structural Analysis*

The structural simulation has been done to determine the stress and displacement in window disc caused by heat loads, i.e., temperature distribution due to electromagnetic heating by Gaussian beam. The stress analysis of RF window has been performed on the disc. In a ceramic window, it is not so much the peak temperature itself which causes a problem, but rather the thermal stress associated with thermal gradients. The stress in the window is the combination of thermal loading of temperature gradients and the mechanical loading because of pressurization and cooling.

III. Simulation Results And Discussions

Transient solver of ANSYS has been used to determine the temperature distribution. The simulation has been carried out considering perfectly edge cooled disc insulated on its two faces and cooled at its edge only. The input parameters are material property, heat flux, and bulk temperature. Parameters for thermal simulation of window materials are given in table I. Input material properties used are listed in the internal reports at MWT/CSIR-CEERI/Pilani/Rajasthan.

TABLE I. Parameters for Thermal Simulation

Parameters	**Value**
Power (P)	1 MW
Frequency (f)	170GHz
Half power beam width (w)	60mm (Nitrides & Beryllia) 20mm (CVD Diamond)
Heat transfer coefficient (α_c)	10000 W/m^2K
Initial Temperature (T_0)	300 K
Pulse duration (t_p)	2s
Aperture diameter (D_A)	125mm (Nitrides & Beryllia) 80mm (CVD diamond)
Disc diameter (D_D)	133mm (Nitrides & beryllia) 88mm (CVD diamond)
Rim	0mm
Waveguide wall thickness (t_w)	4mm
Disc thickness (t)	t_{AlN} = 2.1mm, t_{BeO} = 2.07mm, t_{BN} = 2.03mm, and t_{Si3N4}=2.19mm, $t_{CVDdiamond}$ = 1.85mm

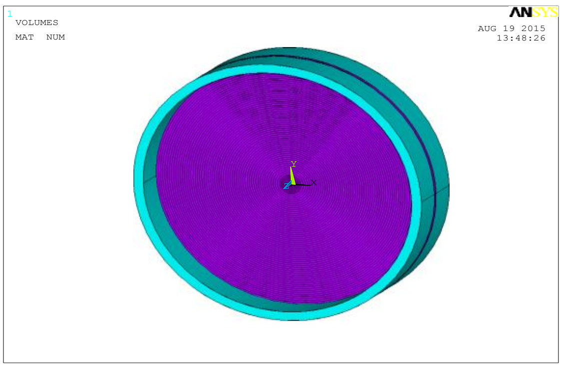
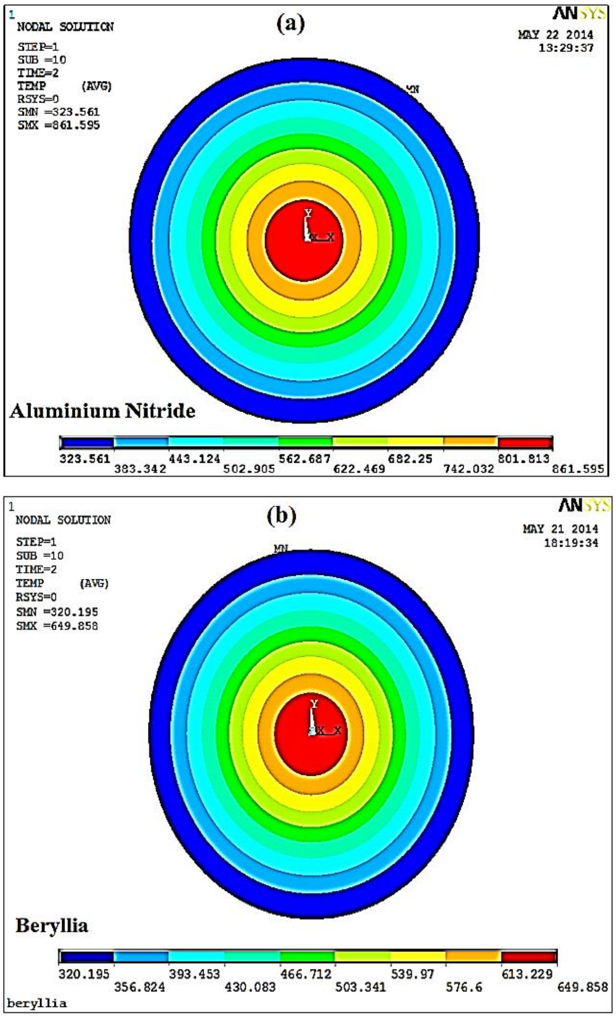


Fig.1. Simulation model of window for assigning Gaussian beam power absorbed in the discs.

For the thermal simulation, dielectric disc is divided in several numbers of rings (Fig.1) and each ring assigned a power density to give input Gaussian distribution of power density as a function of radius.

A. *Thermal Analysis*

The written macros and power density distribution has been crossed checked using the results given in [7]. It was seen that the simulation results (T_{max} =1124 K and T_{min}=308 K) for BN agreed very well with that reported in [10-11]. Then the temperature distribution for 2s heating of AlN, Beryllia, BN and Si_3N_4 respectively was computed and is shown in Fig.2 (a-d).



Maximum (T_{max}) & minimum (T_{min}) temperature obtained through this simulation is 861K & 323K, 650K & 320K, 1910K & 319K, 675K & 304K in the same order. Now these maximum temperatures obtained are compared to the melting/softening point of respective materials to know whether the materials can withstand this temperature or not. It is found that all the four materials can tolerate these

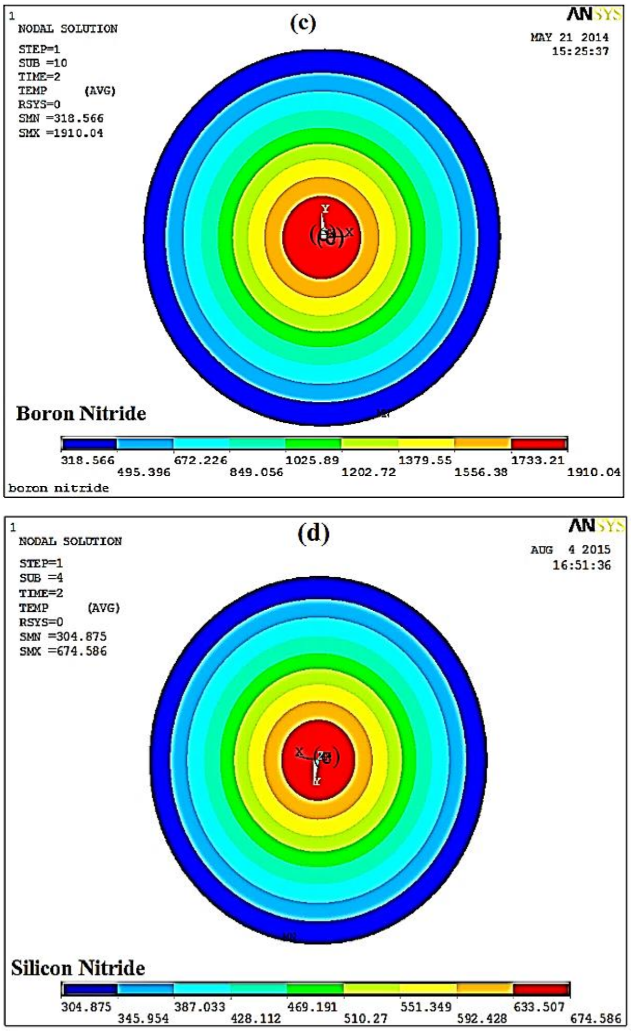


Fig. 2. Nodal temperature (K) distribution for (a) AlN (b) Beryllia (c) BN (d) Si_3N_4.

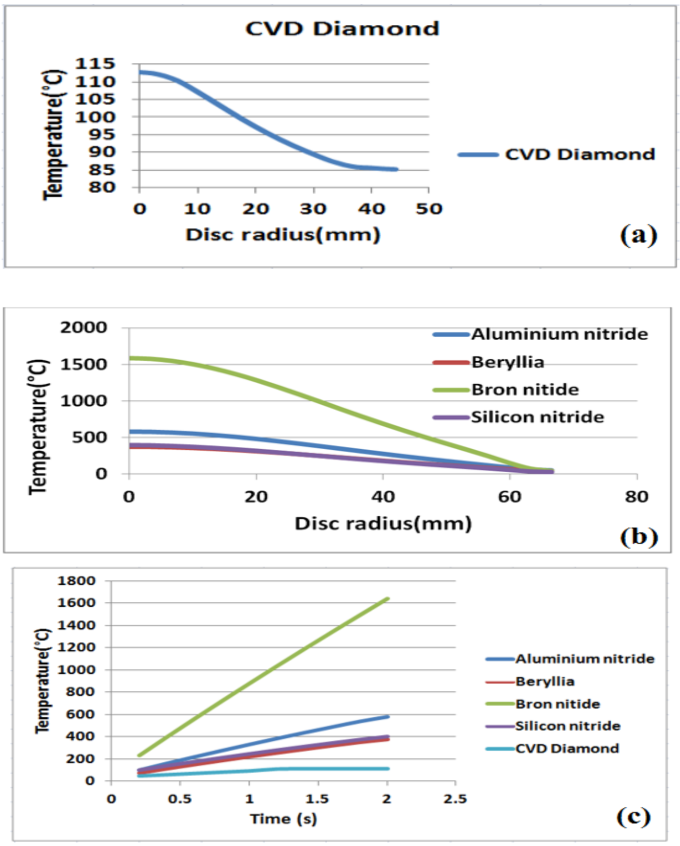


Fig. 3. Radial distribution of temperature for (a) CVD diamond, (b) AlN, BeO, BN and Si_3N_4 (c) Time evolution of T_{max} (centre of the disc).

temperatures as their melting point is well above these values. The calculated ΔT found is 538K, 330K, 1591K, and 371K for AlN, Beryllia, BN and Si_3N_4 respectively. The higher the k/(ε_r tanδ) for a given material lower will be the temperature rise. Beryllia scores the maximum among the four discussed here and hence results in lowest temperature rise/ΔT. On this count it is next only to CVD diamond and Si_3N_4 is next to Beryllia. Fig.3(a & b) show radial temperature distribution on the discs due to the absorption of the Gaussian beam. Fig.3(c) shows the transient behavior of the heating for a period of 2 seconds. It is found that except for CVD diamond steady state is not reached for other materials.

B. *Structural Analysis*

The temperature rise obtained for Beryllia and nitrides are very high. Though they can withstand these temperatures and even higher without melting, their suitability can be ascertained only after estimating the thermal and mechanical stresses. In the ANSYS software thermal analysis file is transformed into structural analysis, as the temperature profile is used as an input for stress analysis. Pressurization (2 atm or more) is also taken as input data for showing differential pressure between air and vacuum sides of the window disc. Fig. 4(a) shows the stress intensity in beryllia and nitrides discs due to pressure differential of 2 atm. It is seen that stress intensity starts at the center of the disc reduces to a minimum at r = 40mm and then again rises to reach a maximum at r = R_A. The lowest stress profile is obtained for BN. It is attributed to the low values of young's modulus and linear expansion coefficient. The maximum average stress intensities calculated for BN, Si_3N_4, AlN, Beryllia are 400.24, 493.78, 674.79, 534.54 MPa. CVD diamond has yielded lowest stress (155MPa) developed and its slope is also smoothest. Si_3N_4 with bending strength of 800MPa is the clear winner wheras BN has bending strength of 80MPa. Also, the softening temperature of BN is higher than Si_3N_4. In fig.4(d) shows the displacement in the waveguide for Si_3N_4 is $0.852*10^{-5}$ mm.

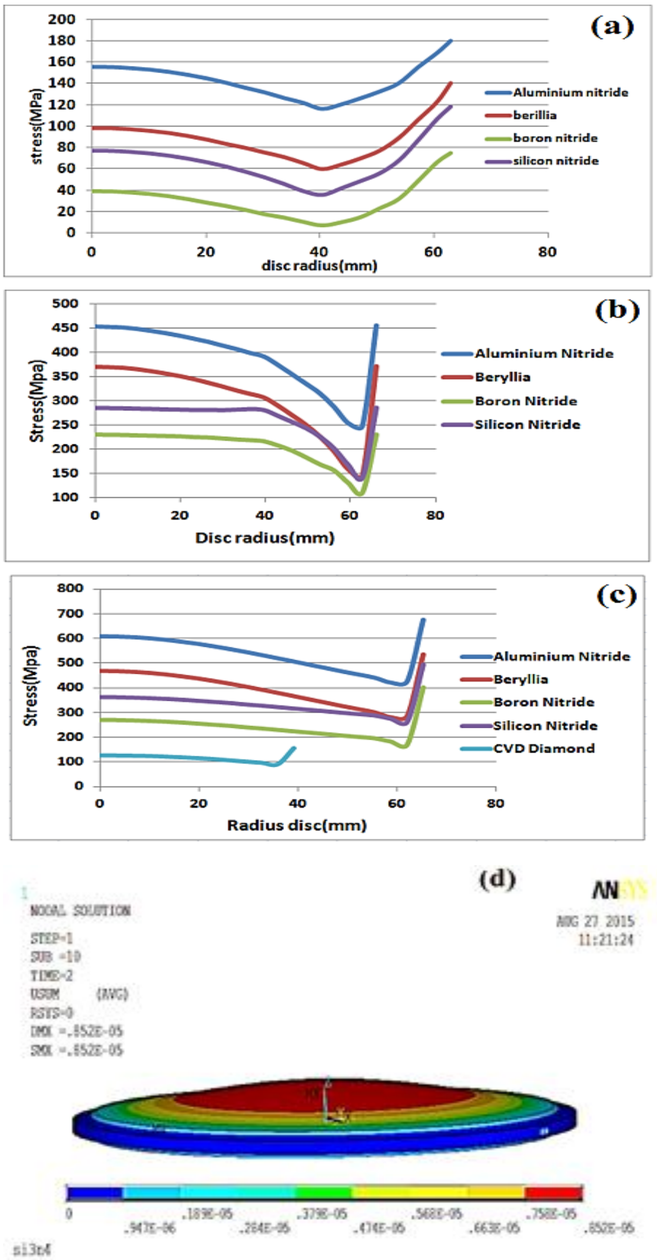


Fig. 4. Radial Stress intensity distribution for (a) Pressurization of 2 atm (b) Temperature from thermal simulation (c) Combined (pressurization and thermal loading) Stress Profile.

Displacement in material atoms is induced because of tensile effect of stress but is very small or negligible deformation to count. An increase in window disc thickness can reduce mechanical stress but would result in increase in temperature rise/ΔT off-setting the improvement in stress performance.

IV. Conclusion

The suitability of materials is performed through thermal and structural simulation. CVD diamond is the best known material for high power window applications and same is found in this investigation. Also, it is found that Beryllia is the next best material through thermal simulation and Si_3N_4 is the next best. Si_3N_4 is the best material than BN through structural simulation. Structural simulation results are preliminary. Further detailed study on modelling of stress aspects of QOWs is required to optimize disc dimensions for enhancing their power handling capacities.

References

[1] J.G.Wegrove et al, "Limit of operation of conventional RF windows for electron cyclotron wave launchers in a reactor",Proc. 14th Symposium on Fusion Technology, Avignon, France, pp 821-827, 1986.

[2] P. Noranjitra et al, " Cryo-cooled high power window for high frequency plasma heating- Thermodynamic study of the single disc concept with liquid nitrogen edge cooling," KfK-Report 4930, Karlsruhe,Germany.

[3] J.P.Calame, D.K.Abe, "Applications of advanced materials technologies to vacuum electronic devices," Proc IEEE, vol. 87, no.5, pp.840-864,May,1999.

[4] CR.Donaldson, Wenlong He, Liang Zhang, and Adrian W.Cross, "A W-band multi-layer microwave window for pulsed operation of Gyro-devices", IEEE Microwave and Wireless Components Letters, vol.23, no.5, pp. 237-239,May 2013.

[5] M.C.Lin, "A multilayer waveguide window for wide-bandwidth millimeter wave tubes", International Journal of Infrared Millimeter Waves, vol.28, pp.355-362, 2007.

[6] Alan M.Cook, Colin D.Joye, Takuji Kimura, Edward l.Wright and Jeffrey P.Calame "Broadband 220-GHz vacuum window for a Traveling-Wave tube amplifier", IEEE Transactions on Electron Devices, vol.60, no.3, pp.1257-1259, March 2013.

[7] V.V.P.Singh, "Analysis of microwave windows for high power microwave tubes", Ph.D. Thesis, B.H.U, Varanasi, India, 2000.

[8] M.Thumm, "MPACVD-Diamond windows for high-power and long pulse millimeter wave transmission, Diamond and Related materials, vol.10, pp. 1692-1699, September 2001.

[9] Y.Gorelov, J.Lohr, R.W.calls and D.Pone, Status report on "Infrareds monitoring of 110 GHz Gyrotron windows at DIII-D", GA-A23981, General Atomics, California, USA, May 2002.Also presented in12thJoint workshop on Electron Cyclotron Emission and ECRH, France, May 13-16,2002.

[10] C.Varandas, F.Serra, Proc. of the 19th symposium on Fusion Technology, Lisbon, Portugal, "Fusion Technology 1996",vol.1, Page 526,September,1996.

[11] M.Thumm, "Development of output windows for high-power long-pulse Gyrotrons and EC wave applications", Int. J. Infr. Millim. Waves, vol.19, no.1, pp.3-14, 1998.

[12] V.V.P. Singh, E. Borie, A.K. Sinha, B.N. Basu, and H.N Bandhopadhyay,"Thermo-mechanical analysis of single-disc edge-cooled silicon nitride millimeter wave window for 200 kW CW gyrotrons," Int. J. infrared & Millimeter Wave, vol.21, no.4, pp.485-504, 2000.