Applications of Advanced Materials Technologies to Vacuum Electronic Devices

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Invited Paper

The applications of advanced engineering materials in modern vacuum electronic devices are reviewed. Unique materials with desirable thermal, mechanical, electrical, and magnetic properties are playing a crucial role in raising the average power capability, bandwidth, and efficiency of microwave and millimeter wave amplifiers and oscillators. Five major materials-related topics and technologies are covered in this article: diamond electromagnetic windows and electrode supports; electromagnetically lossy composite ceramics for control of instabilities; methods of cooling metal structures; pyrolytic graphite beam collectors and electron-gun modulation grids; and rare-earth permanent magnets for confining electron beams. For each topic, this article reviews the background physics, describes the importance of the technology to vacuum electronics, presents illustrative examples of how such technologies perform, and reviews current results from the literature.

Keywords—Dielectric materials, electron tubes, materials science and technology, microwave technology.

I. INTRODUCTION

Microwave and millimeter wave amplifiers based on vacuum electronics are the technology of choice when very high average or peak power production is required. Vacuum electron transport can propagate large amounts of electron beam power without the production of resistive heat that occurs in solid-state devices, and the high electron velocity in vacuum allows larger interaction structures before transit time phenomena or electrical breakdown can affect performance. Waste energy present in the electron beam after electromagnetic energy has been extracted can be deposited over extended collection surfaces remote from the area where amplification takes place, simplifying thermal management. The current state-of-the-art includes broadband amplifiers that can generate hundreds of watts of continuous wave power over several octaves, as well as narrower band devices that can generate multimegawatts of average power at frequencies up to 100 GHz. Advanced materials are used extensively in all classes of vacuum electronic devices in a wide variety of applications, including thermal management, the control of electromagnetic instabilities, air-vacuum interfaces, and the focusing of electron beams. As commercial and defense needs expand into the millimeter wave frequency regime, materials will continue to play a significant role in improving the efficiency, compactness, and power-producing capabilities of vacuum electronic devices.

As the frequency increases, the average power capability of any given class of amplifier technology tends to decrease. Generally speaking, the linear dimensions of the amplifying structures tend to vary proportional to $1/f$, where $f$ is the frequency, to avoid transit-time effects on the charge carriers during single cycles of the electromagnetic wave. Since power is dissipated on surfaces, average power capability thus varies as $A/f^2$, where $A$ is a proportionality constant that depends on the device type. The comparatively large value of $A$ that is possible in vacuum electronic devices is a decided advantage at high frequencies.

The present state of the art for average power production in vacuum electronic devices is plotted as a function of frequency in Fig. 1 [1]–[4]. Referring to the figure, we see that the power capabilities of the linear beam amplifiers—helix and coupled-cavity traveling-wave tubes (TWT’s) and klystrons—exhibit this roughly $1/f^2$ decline at frequencies above a few gigahertz. In these devices, heat dissipation on increasingly small surface areas becomes the dominant issue as the frequency increases (at millimeter wavelengths, it also becomes increasingly difficult to focus and confine the electron beam). Over the past 15 years, the progress in the power performance capabilities of these devices can be largely attributed to the advent of improved heat dissipating materials; system volumes and weights have also benefited from higher performance magnetic materials.

While advanced materials can be used to increase the power capability of a device by increasing the tolerable heat dissipated per unit area, another method of producing
high power at higher frequencies is to use devices with interaction structure sizes that are considerably larger than conventional wavelength-based resonators or frequency-based transit time limits. In the gyrotron oscillator (Fig. 1), the onset of the $1/f^2$ dependence is delayed through the use of overmoded cavities, which allow higher frequency operation to be achieved without the proportional reduction in cavity surface area (which would increase the dissipated power density). While heat dissipation is still a concern, mode competition issues eventually come to dominate at the higher frequencies and the performance falls at a very rapid rate. Hybrid devices, such as the gyroklystron (amplifiers based on gyrotron technology), operate at more moderate levels of overmoding and are thus limited by a combination of mode competition and thermal dissipation. For both the gyrotron and the gyroklystron, advanced materials have made significant impacts in controlling unwanted electromagnetic modes and instabilities as well as improving thermal management.

Finally, klystrodes, located on the low frequency end of Fig. 1, have a resonator structure similar to klystrons but employ a biasable grid at the cathode to modulate the electron beam. These devices exhibit a very sharp fall-off in power capability near 1 GHz due to electron transit-time effects in the cathode-to-grid gap. In this case, the device is dominated by materials issues of mechanical grid strength and fabrication processes.

Advanced engineering materials with desirable thermal and electrical properties have played a major role in raising the average power-production levels of all of the vacuum electronic devices shown in Fig. 1. Advanced materials have also played a substantial role in meeting related goals, such as the need for high overall system efficiency, improved bandwidth, and compact system size and weight. In this article, several materials science technologies and their applications to vacuum electronic devices will be reviewed in detail. In writing this article, an emphasis has been placed on emerging technologies that have great promise to continue the advancement of performance capabilities into the future.

This article is organized into sections devoted to different classes of materials. In each case, we review the physical basis of the technology, describe how it is important to vacuum electronic devices, provide illustrative examples of how such technologies perform, and describe specific results from the literature. Theoretical calculation is provided to expose the reader to the specific advantages of the materials and to illustrate the design tradeoff process. We hope that by providing this level of detail, readers in other fields of engineering will be able to evaluate these materials and technologies for their specific needs and applications.

In Section II, we describe the application of diamond-based materials to electromagnetic windows and internal electrode and circuit supports. The high thermal conductivity of diamond directly reduces the thermal management problems which limit average power. Therefore, in gyrodevices and TWT’s, diamond can raise the attainable average power at a given frequency, extend the upper limit on frequency capability, and improve device lifetimes. In Section III, we investigate the applications of ceramic microwave absorbers in vacuum electronic devices. Microwave absorbers are used to control cavity quality factors in klystrons and play a critical role in suppressing electromagnetic instabilities in large bandwidth devices (such as TWT’s) and in devices employing overmoded structures (such as gyrotrons and gyroklystrons). Improved absorber technology would extend the bandwidth capability of TWT’s and enable the utilization of a greater amount of overmoding in gyroklystrons. Section IV describes technologies for cooling metal structures, including flow boiling and porous metal cooling. These techniques allow the thermal power density in electron beam collectors and electromagnetic interaction structures to be raised well above conventional limits. As a consequence, one can increase average power capability and reduce the physical size and weight of all types of vacuum electronic devices. In Section V, pyrolytic graphite is explored; the material has unique high-temperature capabilities and highly anisotropic thermal and electrical properties that can be exploited in high average power devices where high efficiency is also needed. Applications include TWT’s and gridded devices such as klystrodes. Finally, in Section VI, we explore the application of high energy density, high coercivity permanent magnets. Such magnets can generate intense magnetic fields with complex spatial distributions unattainable by other means for use in high frequency, high efficiency, lightweight amplifiers. Devices benefiting from this technology include TWT’s, klystrodes, and low-to-moderate frequency gyroklystrons.

II. APPLICATIONS OF DIAMOND

Two of the most important applications for electromagnetically transparent (low loss) dielectric materials in vacuum electronic devices are windows and electrically insulating supports. Windows provide a physical barrier between the internal high vacuum of the device and the external (typically atmospheric pressure) environment, while
allowing the free transmission of RF power. The window material must be strong enough to withstand this pressure difference. In addition, any electromagnetic losses within the dielectric will result in volumetric heating and differential thermal expansion, which will cause additional mechanical stress. Finally, the impedance mismatch caused by the transition between free space and the dielectric constant of the window material causes reflections that must be canceled with matching techniques over some appropriate bandwidth. The ability to achieve an acceptable wideband match decreases as the dielectric constant of the window material rises. Thus, the ideal window material should possess low dielectric losses, high mechanical strength, high thermal conductivity, low thermal expansion, and a low dielectric constant.

In the case of electrically insulating supports for structures subjected to heating by beam impingement or induced RF currents (e.g., beam collection electrodes, a TWT helix, beam intercepting probes, etc.), similar properties are required as in the window problem. High thermal conductivity and good resistance to thermal shock are universally required. If the supports themselves are also subjected to RF fields, then low dielectric losses and a low dielectric constant are needed to minimize impedance loading on the RF interaction circuit and to reduce spurious heating of the supports.

Until recently, the material of choice for these applications was beryllium oxide (BeO), which has the highest thermal conductivity of any oxide or nitride ceramic and is readily available. It was long recognized that diamond, which has the highest thermal conductivity and hardness of all known materials, would be an ideal replacement for BeO on the basis of thermal, mechanical, and electrical properties [5], [6]. A comparison of the properties of BeO and diamond is shown in Table 1. An additional motivation for replacement is due to safety issues; BeO is highly toxic and requires special precautions for fabrication, handling, and disposal, while diamond is completely harmless. However, the great expense of natural diamonds and the unavailability of large sizes regardless of cost considerations made this transition difficult. Synthetic diamonds produced by the ordinary high pressure process, although inexpensive, are generally too small to be of value for microwave applications.

In the last ten years, the advent of high deposition-rate, chemical vapor deposited (CVD) diamond has dramatically altered the situation. In a typical process [7], mixtures of hydrocarbons such as methane and gaseous hydrogen at a total pressure in the 50–100 torr range are converted into a plasma by a microwave discharge. The high temperature plasma (5000–7000°C) decomposes the hydrocarbon gas to form carbon radicals. These radicals bond to each other to form a deposit of carbon on a substrate, which is typically a silicon wafer. Thermodynamics cause the majority of the carbon to be deposited with sp² hybridization (graphite) instead of sp³ hybridization (diamond). However, atomic hydrogen present in the plasma preferentially removes the more reactive sp² bonded carbon by reconverts these atoms to hydrocarbon gas, allowing the growth of a nearly pure diamond film. The substrate is maintained at a relatively low 900–1000°C to prevent thermally activated conversion of the deposited diamond to graphite. Diamond deposition rates in the range of 10–50 μm/h are possible with careful control of the process variables. This process can economically produce disks of polycrystalline diamond up to 10 cm in diameter and several millimeters thick. Other shapes, such as small-diameter cylindrical rods and thin wedges, can be produced by machining bulk forms manufactured by the CVD process. Although the diamond materials originally produced by the CVD process contained large amounts of graphite and hydrocarbon impurities that caused unacceptable dielectric losses, modern diamond synthesis procedures have been greatly improved. New grades are now available [8] with losses comparable to those of high quality BeO. The large sizes and suitable properties of CVD diamond materials have promoted their application in high average power RF sources and have opened up new regimes of performance not previously obtainable with conventional materials [9]. The following two subsections will describe in detail the underlying engineering and physics issues associated with using diamond for electromagnetic window and electrode support applications. The general physical aspects of the discussion are relevant to all types of natural and synthetic diamond, although the specific economic considerations and physical properties will vary. Relevant experimental progress in these applications, obtained from the open literature, will be described.

### A. Electromagnetic Windows

An electromagnetic window in a vacuum electronic device serves to isolate the high vacuum present inside the device from the outside world, while allowing electromagnetic energy to pass through the structure without significant degradation. Windows can be used in many possible configurations depending on the required quality and bandwidth of impedance matching. For narrowband operation, simple disks that are even multiples of a half-

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<th>Table 1</th>
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<td>Comparison of BeO and CVD Diamond properties at 25°C</td>
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<tr>
<td>Property</td>
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<tr>
<td>Density (g/cm³)</td>
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<tr>
<td>Specific Heat (J/g·K)</td>
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<td>Thermal Conductivity (W/m·K)</td>
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<td>Coefficient of Thermal Expansion</td>
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<td>Loss Tangent</td>
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<td>Bulk Dielectric Strength (kV/cm)</td>
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Fig. 2. Diagram of a pillbox window assembly and an equivalent transmission line model.

Fig. 3. Calculated bending stresses in a 2.54-cm diameter diamond and BeO disk windows subjected to atmospheric pressure as a function of thickness.

wavelength thick (measured in the dielectric) are placed in a circular waveguide. If the window is made very thin, then nonresonant, broadband operation can be achieved. Alternatively, windows can be located within a matching structure. Such structures, consisting of waveguide steps and transitions that create impedance transformations and reflections, cancel the normal window reflections over some bandwidth. One example of the latter configuration, known as a “pillbox” window [10], [11], is shown schematically in Fig. 2, along with an equivalent transmission line model. The window of thickness $h$ is located within a length of circular waveguide, and it is brazed along its circumference to create a vacuum seal. At a distance $d$ from either face of the window, there is an abrupt, step transition to rectangular waveguide with appropriate dimensions for TE$_{10}$ fundamental mode propagation.

In operation, an electromagnetic wave entering from the left in the rectangular guide (impedance $Z_1$, propagation factor $\beta_1$) encounters the transition to circular waveguide. A significant fraction of the power will mode-convert to the TE$_{11}$ circular waveguide mode (impedance $Z_2$, propagation factor $\beta_2$), but there are also evanescent (nonpropagating) modes in the vicinity of the junction which are required to match boundary conditions and are represented by a shunt imaginary susceptance $jB$. A reflection is created by two effects: the presence of the shunt susceptance and the impedance mismatch between $Z_1$ and $Z_2$. In practice, the reflection from the susceptance dominates. As the TE$_{11}$ circular waveguide mode encounters the window (internal impedance $Z_3$, propagation factor $\beta_3$), additional reflections are created at each face. Finally, the wave encounters an abrupt transition back to rectangular guide that triggers more reflections and causes the power to mode-convert back to the TE$_{10}$ rectangular waveguide mode and propagate toward the right.

In this simple pillbox geometry, overall reflections are eliminated by destructive interference of the various reflections present within the structure. The rectangular waveguide dimensions are assumed to be fixed by standard sizes for the operating frequency band. For a particular window dielectric constant (which controls $Z_3$ and $\beta_3$) and thickness, the designer can adjust the radius of the circular guide and the spacing, $d$, to eliminate the reflection at any given frequency within the operating band. The magnitude of $jB$ is controlled by the circular guide radius, and $d$ essentially controls the phasing between the various reflections. In general, the bandwidth of the resulting match increases as both the window thickness and dielectric constant decrease.

The advantage of CVD diamond in this scenario arises from its high bending strength, which is in the range of 200–500 MPa and is a factor of two to three times higher than BeO [12]. Thus, windows composed of high-strength diamond can be made thinner than those of BeO, which will reduce reflections in unmatched window applications and increase the bandwidth in pillbox configurations [11]. The dielectric constant of diamond is somewhat smaller than that of BeO, which is also advantageous. As an illustrative example, we will consider a 2.54-cm diameter window designed to operate in X-band (8.0–12.4 GHz). To compute the stress in a window due to atmospheric pressure, one has to make some assumptions of how the window is supported. Typically the circular guide material is soft, thin copper to avoid residual stress from brazing due to differences in thermal expansion. Under these conditions, the window can be assumed to be simply supported along its edge. The bending stress in a such a thin disk of diameter $D$ and thickness $h$, under uniform surface pressure $P$, is given by

$$
\sigma_b = \frac{3(3+\nu)PD^2}{32h^2}
$$

where $\nu$ is Poisson’s ratio [12], [13]. Poisson’s ratio varies between 0.1 and 0.2 for different types of diamond; the effect is weak since $\nu$ is added to three. Fig. 3 shows the results of a stress calculation for a 2.54-cm diameter window as a function of thickness for $\nu = 0.2$ and atmospheric pressure (101 kPa) loading. Also plotted are the fracture strengths of BeO and diamond, along with the working strengths of each material assuming a safety factor of ten (critical since a window failure is catastrophic). Clearly, the stress builds very quickly as the thickness decreases, but the higher strength of diamond allows a thinner window. For BeO in this diameter, a thickness of 1.3 mm (0.050 in) is typical, while with diamond a thickness...
of 0.635 mm (0.025 in) results in acceptable stresses. In the future, even thinner diamond windows should be possible. Single crystal natural diamond has a fracture stress of 2.8 GPa, and although polycrystalline specimens will generally have inferior properties, experience with Al₂O₃ and other materials indicates that polycrystalline ceramics can often approach one-third of the single crystal value. It seems reasonable to assume that a fracture strength of 0.9 GPa should be attainable in future CVD diamond materials, corresponding to a 0.30 mm (0.012 in) thick window and a safety factor of ten.

The unmatched reflections associated with TE₁₁ mode propagation through the 1.3-mm thick BeO and the 0.635-mm thick diamond windows (in 2.54-cm diameter circular waveguide) as a function of frequency are shown in Fig. 4. Over 50% of the power is reflected by the BeO, while 16–20% of the power is reflected by the diamond. With such relatively low reflection, the thinner diamond window may be usable without matching for some applications. The plot also displays the results of matching with a pillbox design using WR90 rectangular waveguide for the input and output guides and optimizing over the 9–11-GHz band for each of the two cases. The diamond case has about 2.5 times the bandwidth of the BeO case. This example clearly illustrates the utility of diamond to enhance the bandwidth of window assemblies.

Of much greater importance is the ability to transmit higher RF powers with diamond compared to BeO. An electromagnetic wave passing through a dielectric medium deposits a power per unit volume according to

\[ P = \frac{1}{2} \varepsilon \omega \varepsilon'' E^2 \]

where \( \varepsilon' \) is the real part of the dielectric constant, \( \varepsilon'' \) is the imaginary part of the dielectric constant, \( \tan \delta = \varepsilon'' / \varepsilon' \) is the loss tangent of the material, \( \varepsilon_0 \) is the permittivity of free space, \( \omega \) is the angular frequency of the radiation, and \( E \) is the local electric field. Such a volumetric power dissipation will lead to heat deposition in the window, which must be removed. Two concepts have been employed to cool windows. The simplest is edge cooling, in which heat is transported radially outward toward the brazed circumference of the disk by thermal conduction through the window material, where it is removed by fluid cooling of the metal that makes up the waveguide [14]. The second method of heat removal is face cooling, in which the window is composed of a pair of disks separated from each other by a layer of flowing coolant such as freon or liquid nitrogen. This method has been used in 1-MW continuous wave, 140-GHz output windows [15]. Edge cooling is preferred for nearly all ordinary applications due to its simplicity, so we concentrate on this method in our illustrative example.

To compute window heat loading, one assumes that the electric field for the TE₁₁ mode is of the form

\[ E(r, \theta) = \frac{2E_0 J_1(x'_{11} r/a)}{x'_{11} r/a} \sin \theta \frac{\partial}{\partial r} - \frac{2E_0 J_1(x'_{11} r/a) \cos \theta}{\partial \theta} \]  

in polar coordinates, where \( E_0 \) is the peak field amplitude at the center of the window and \( a \) is the window radius [16]. The value of \( E_0 \) is related to the square root of the power being transmitted through the guide and the geometry; for 1 W of average power in a 2.54-cm diameter guide, \( E_0 = 2076 \) V/m. The electric field pattern of (3) is applied to (2), and the two-dimensional (2-D) heat equation

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} = \frac{U_Y}{\kappa} \]

where \( \kappa \) is the thermal conductivity, is solved for the temperature \( T \) over the window using finite difference or finite element techniques. The implicit assumptions are that the window is sufficiently thin to avoid significant field variation in the axial direction, that the edge at \( r = a \) is held at a fixed temperature, and that the temperature rise is small enough to cause minimal changes in thermal conductivity and dielectric loss. Although the field of the TE₁₁ mode is not axisymmetric, the radial temperature distribution created by it displays a high degree of circular symmetry as a result of thermal diffusion. A plot of the temperatures obtained with this analysis is shown in Fig. 5 for each of the window materials, assuming 250 kW of average power transmission at 10 GHz. The diamond window peak
temperature rise (relative to the outer edge) reaches 9.4°C, which is about a factor of ten lower than the 90°C rise found in the BeO design. The thermal conductivity of BeO will decrease by about 25% over the temperature range encountered in this simplified example, compared to an 8% drop that occurs in the lower temperature diamond case. This makes the use of diamond even more advantageous.

In a ceramic window, it is not so much the peak temperature itself which causes a problem, but rather the thermal stresses associated with thermal gradients. If the 90°C temperature rise in the BeO window was spatially uniform, it would not be a cause for great concern since it is nowhere near the softening point. To estimate the stresses for nonuniform temperatures, one can assume that there is no external force applied to the outer circumference as a first approximation. As in the previous force computations, this assumption is justified if the supporting pillbox waveguide is thin and made of a soft metal. The radial stress, $\sigma_r$, and the tangential (hoop) stress, $\sigma_t$, at any point [17] are given by

$$\sigma_r = \alpha Y \left( \frac{1}{\eta^2} \int_0^\alpha \Gamma(r')r' \, dr' - \frac{1}{\eta^2} \int_0^\alpha \tilde{T}(r')r' \, dr' \right)$$

$$\sigma_t = \alpha Y \left( -\tilde{T}(r) + \frac{1}{\eta^2} \int_0^\alpha \tilde{T}(r')r' \, dr' + \frac{1}{\eta^2} \int_0^\alpha \tilde{T}(r')r' \, dr' \right)$$

where $\alpha$ is the thermal expansion coefficient, $Y$ is the modulus of elasticity, and $\tilde{T}(r')$ is the radial temperature profile calculated previously. The hoop stresses are of the greatest concern, since beyond a certain radius they can trigger tension (represented by a positive stress), and ceramics are weakest when in tension. In Fig. 6, the hoop stresses as a function of radius are plotted for the BeO and diamond window designs, using their respective temperature profiles. For the example in question, the BeO window would fail by fracture (safety factor $\approx 1$), while the diamond window has a factor of safety of at least 20. This example illustrates the enormous advantage that diamond has over BeO for high average power windows.

A useful power handling capability index for window materials can be formulated with the analysis presented in this section, assuming that thermal fracture (as opposed to melting) is the dominant failure mechanism. The temperature rise is proportional to the ratio of the absorbed power divided by the thermal conductivity ($\varepsilon\tan\delta/\kappa$), and the thermal stress is the proportional to the product of this temperature rise with the thermal expansion coefficient and the modulus of elasticity. Thus, the thermal fracture power-handling index, $P_{fr}$, is proportional to the ratio of the working stress limit for the material divided by the thermal stress, or

$$P_{fr} = \frac{\sigma_{wK}}{\alpha Y \varepsilon \tan\delta}.$$  (7)

Table 2 lists this figure of merit for several different ceramic materials, based on properties available in the literature. The superiority of diamond over all competing materials is clear; its figure of merit is 25 times higher than that of BeO. Although Si$_3$N$_4$ also scores relatively high [18], it is due more to a high stress limit and low thermal expansion, rather than high thermal conductivity. A window of Si$_3$N$_4$ would thus run considerably hotter than one made of diamond or BeO under identical transmitted powers. Thus a second figure of merit should be proportional to the reciprocal of the temperature rise, or

$$P_{temp} = \frac{\kappa}{\varepsilon \tan\delta}.$$  (8)

This is also listed in Table 2, along with the product of the two figures of merit. Diamond is the clear material of choice by any measure, a conclusion in agreement with similar published figure of merit studies [9]. Accordingly, diamond windows are being evaluated for use in high-power millimeter wave sources (100–170 GHz) producing 0.5–1.0 MW continuous wave output power for fusion plasma heating [8], [14]. They are finding immediate use in moderate power commercial microwave amplifiers for communications and radar applications [19].

### B. Electrically Insulating Electrode Supports

Consider the idealized geometry of Fig. 7, in which a metal cylindrical shell electrode is supported inside a vacuum jacket by dielectric wedges. If RF fields are present inside the supported cylinder, or if electron beam interception occurs, heat will be generated which must be conducted outward toward the vacuum jacket. This general type of geometry, which could represent a biased beam collection electrode or the helix of a TWT, occurs quite

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**Table 2**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Fracture Index $P_{fr}$ (a.u.)</th>
<th>Temperature Index $P_{temp}$ (a.u.)</th>
<th>Product of Indices $P_{fr} \times P_{temp}$ (a.u.)</th>
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<tbody>
<tr>
<td>CVD Diamond</td>
<td>145</td>
<td>89</td>
<td>13,900</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>29</td>
<td>3.7</td>
<td>110</td>
</tr>
<tr>
<td>BeO</td>
<td>5.1</td>
<td>9.3</td>
<td>47</td>
</tr>
<tr>
<td>AlN</td>
<td>3.4</td>
<td>2.4</td>
<td>8.2</td>
</tr>
<tr>
<td>Sapphire</td>
<td>1.6</td>
<td>2.0</td>
<td>3.2</td>
</tr>
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frequently in vacuum electronic devices. It represents, at least in principle, a good application for diamond, which has excellent thermal conductivity and acceptable electrical breakdown strength [20].

The thermal analysis of such a structure can be broken down into two regions: the metal tube and the ceramic wedge. Azimuthal periodicity and symmetry allow one to model only one-sixth of the geometry (with proper mirror boundary conditions), as indicated in Fig. 7. A uniform heating power density is assumed to impinge upon the inner surface of the supported cylinder, and the temperature at the outer edge of the insulator is assumed to be fixed. In many devices there is no rigid attachment between the insulator and the inner tube. Instead, the inner tube/insulator assembly is made oversized, and the outer jacket is slightly warmed and quickly inserted over the inner assembly [21]. As the jacket cools and contracts, radial mechanical pressure develops between the components which ensures a reasonable thermal contact between the different materials, albeit with a junction thermal resistance that is difficult to predict. In practice, these junction thermal resistances are measured experimentally. It is also possible to forcibly insert a slightly oversized assembly at room temperature, provided that the inner metal is thin enough to slightly deform. With proper design, the deflection of the metal can produce a controlled compressive stress in the insulators that creates an acceptably low junction thermal resistivity. An alternative method of assembly utilizing ceramic-to-metal brazing to join the parts together, which virtually eliminates junction resistance. In this case, care must be taken to ensure complete bonding between the parts, and differential thermal expansion between the metal and insulators can complicate fabrication.

In the case of nonbrazed (pressed-fit) construction, both BeO and another material, anisotropic pyrolytic boron nitride (APBN) [20]–[22], are widely employed at present. APBN has a hexagonal, layered structure with high thermal conductivity in the plane of the layers (basal plane). Typical values for bulk commercial material at room temperature are 200 Wm\(^{-1}\) K\(^{-1}\) along the basal plane and 1.5 Wm\(^{-1}\) K\(^{-1}\) in the perpendicular direction [23]. For electrode support applications, APBN is always oriented with the layers placed parallel to the anticipated thermal gradient (the radial direction in Fig. 7). Higher thermal conductivities (about 400 Wm\(^{-1}\) K\(^{-1}\) in the basal plane) have been achieved in very thin, highly ordered APBN films [24], but these superior characteristics are difficult to reproduce in sizes and in quantities suitable for use in most vacuum electronic devices. APBN lacks the mechanical strength of BeO and diamond, but this can actually be an advantage in the forced-insertion assembly technique since some compliance in the insulator is desirable. In the case of brazed construction, BeO is the standard material since it has high thermal conductivity and can be easily metalized and bonded with normal molybdenum manganese-based techniques.

Diamond has the potential to replace these more conventional materials in selected electrode support applications. To explore the impact of diamond, consider an example based on Fig. 7 with dimensions relevant to a Ka-band (26.5–40 GHz) device [25]. Representative dimensions are an inner metal tube diameter of 1.02 mm (0.040 in), a metal wall thickness of 0.152 mm (0.006 in), and dielectric wedges 40 degrees in azimuthal extent by 0.76 mm (0.030 in) radial. At the junction with the metal tube, the dielectric wedges are 0.51 mm wide (0.020 in). The thermal analysis problem was solved using finite difference techniques, assuming a tungsten tube. The variation in the thermal conductivity with temperature for each material was included in the calculations. For the brazed construction in BeO and diamond, perfect thermal contact was assumed at the joint between the tungsten and the insulator. In the nonbrazed case with BeO, APBN, and diamond, a junction thermal resistance was included in the calculation at this location [20], [22]. A typical resistance value for a BeO-tungsten pressed-fit is \(2.8 \times 10^{-6} \text{ Km}^2 \text{ W}^{-1}\), which is achievable at an interface pressure of 136 MPa (20,000 psi). To reliably reach this level of thermal contact, the tungsten is generally given a thin copper coating prior to making the press fit. The ductile copper flows under pressure and helps fill irregularities on the component surfaces. For APBN with copper-coated tungsten, a representative resistance value is \(3.6 \times 10^{-6} \text{ Km}^2 \text{ W}^{-1}\), which occurs at a reduced pressure of 68 MPa (10,000 psi) as a result of the lower compressive strength of the material. Pressed-fits between diamond and copper-coated tungsten typically achieve a very low junction resistance of \(1.2 \times 10^{-6} \text{ Km}^2 \text{ W}^{-1}\) at 136 MPa (20,000 psi).

The results of the calculations are shown in Table 3, assuming an integrated power deposition per axial length of 320 W/cm along the inner surface of the metal tube. As expected from the geometry, the hottest point is located on the inner wall of the metal cylinder at the point furthest from a support. This temperature rise, relative to the outer edge of the support, is listed as \(\Delta T_{\text{max}}\) tube-to-wall in the table. Also listed in Table 3 are the separate temperature rises that make up this total, which are the temperature rise along the metal tube from the hottest point to the point nearest the insulating support (\(\Delta T_m\)), the step temperature rise associated with the metal-to-support joint (\(\Delta T_j\)), and the temperature rise across the support itself (\(\Delta T_k\)). For the brazed construction, the peak temperature rise \(\Delta T_{\text{max}}\) of the diamond supported case is about one-half as large as the BeO case. A substantial amount of the total temperature...
rise is associated with the tungsten tube itself, which ultimately limits the improvement obtainable with a high thermal conductivity support. However, a factor of two reduction in peak temperature for a given power density is a great improvement. This reduction in temperature can greatly improve the lifetime and reliability of the structure. Alternatively, the incident power density can be doubled by using diamond supports (for any fixed value of tolerable temperature rise). For the nonbrazed (pressed-fit) cases, a considerable temperature differential exists across the metal-to-support junction. The junction temperature step can amount to a significant fraction of the total temperature; it typically increases the maximum temperatures over the corresponding brazed cases by about 70%. Pressed-fit diamond would still offer about a 50% reduction in peak temperature compared to pressed-fit BeO, and a 57% reduction compared to pressed-fit APBN. But as a result of junction thermal losses, pressed-fit diamond is only marginally better than brazed BeO. In designing actual devices, one must remember that the lower temperatures afforded by diamond in the various configurations must be weighed against the greater difficulty in fabrication and assembly compared to APBN or BeO.

In cases where there are RF fields in the vicinity of the supports, as in a helix TWT, there are advantages in reducing the total amount of dielectric present in the circuit. These advantages include avoiding impedance loading of the RF circuit and maintaining an adequate distribution of electromagnetic fields in the areas where the electron beam resides (preserving beam-wave interaction) [21]. The results of a thermal analysis using diamond supports one-third as wide as the standard BeO case are also shown in Table 3. Both brazed and pressed-fit cases are listed. The temperature levels are now comparable to corresponding BeO cases, but the total volume of dielectric is greatly reduced. A pressed-fit TWT using narrow diamond supports has been constructed and described in the literature by Tamashiro and Aldana [26]. The development of a cost-effective process to manufacture a brazed helix TWT with diamond supports, which would take full advantage of diamond’s thermal properties, continues to be an area of active research.

III. APPLICATIONS OF MICROWAVE ABSORBING DIELECTRICS

Microwave absorbers are employed in microwave tubes for a variety of reasons. In TWT’s, they are often used to provide isolation between the output and input regions of the tube, preventing feedback and oscillation. In other devices, they can prevent self-oscillation due to inadvertent cavities formed by beam tunnel transitions, suppress higher order modes within the principal cavities, or reduce backward-wave interactions. Microwave absorbers can also decrease the quality factor $(Q)$ of the operating mode in input and buncher cavities. Finally, microwave absorbers are often employed to reduce reflections due to higher order modes at coupling ports, to provide filtering at specific frequencies, and to prevent mode conversion. Microwave absorbers are characterized by their complex relative dielectric constant $\varepsilon^*$, where, by convention, $\varepsilon^* = \varepsilon' - j\varepsilon''$. Such a formulation assumes sinusoidal steady-state fields with $e^{j\omega t}$ time variation. In general, the complex dielectric constant is a function of frequency.

Microwave absorbers must be placed directly inside the vacuum envelope (as opposed to placing them outside through the use of coupling slots and windows) in a number of circumstances. These include cases when extremely heavy loading (low $Q$) is required, when the loading must occur over a broad frequency range, when the region to be loaded occupies a distributed area of the tube or in an inaccessible place, or when reflections and/or perturbations from slots or windows are intolerable. Since most cathodes used in power tubes require base pressures in the high $10^{-9}$ to low $10^{-8}$ torr region, the vacuum properties of internally placed absorbers are often just as important as the dielectric properties.

In the following subsections, a variety of vacuum electronic applications of microwave absorbers will be de-
while in Fig. 8(c), rings made of lossy material are alternated with metal rings. The spiral wire system is based on a scheme developed by Bell Laboratories in the 1950’s for the long-distance transmission of high-radial-mode-number circular electric modes for microwave communications applications [28]. In both cases, the axial electric field of TM modes causes the leakage of energy into the dielectric, producing attenuation. The spiral wire case requires a dielectric with a low to moderate $\varepsilon’(4-9)$ and a high $\tan \delta(0.2-0.5)$ for best performance. Accurate control of the dielectric properties is not important because the wire partially isolates the absorber from the fields within the beam tunnel.

In the alternating ring case, the effect can be made either resonant or nonresonant depending on the amount of loss present. Relatively low losses allow each slot to behave like a radial transmission line with a short at the far end. Such a structure will have a resonant frequency determined by the dimensions of the structure and the real part of the dielectric constant, $\varepsilon’$, while the bandwidth can be simultaneously controlled by the imaginary part, $\varepsilon’’$. Accurate control of the dimensions and dielectric constant is an important requirement in this resonant case. If the loss is made sufficiently high, the fields entering the slot will be strongly attenuated as they travel radially outward, so only insignificant amounts of power can return to the drift tube; under these circumstances the structure is nonresonant. However, excessively high values of either $\varepsilon’$ or $\varepsilon’’$ will prevent significant power from entering the slot in the first place by creating metal-like reflections.

The power-handling capability required of the dielectrics depends on the application. When suppression of oscillation (rather than the absorption of substantial power) is the goal, all of these drift tube configurations require only a low power-handling capability. In high-power klystrons, there can be a second harmonic component of the beam modulation that is not cut off by the metal structures of the microwave circuit. Although the conversion to second harmonic may only represent 1–2% of the overall fundamental power, the absolute quantity of power to be dissipated can be large in high average power devices.

One relatively new type of microwave amplifier that requires careful attention to dielectric loading is the gyroklystron [29]. A gyroklystron combines the bunching and energy-extraction mechanisms of the gyrotron with the amplifying configuration of the klystron. The gyroklystron employs a spiraling electron beam in a magnetic field. An input cavity provides transverse velocity modulation, and ballistic bunching occurs in phase angle along the Larmor orbits as the beam moves through a series of beam tunnels and bunching cavities. In the output cavity, energy is coherently released through the cyclotron maser instability (a relativistic effect). Gyroklystrons can operate with overmoded cavities and drift tubes, providing superior power-frequency characteristics compared to other types of amplifiers. Gyroklystrons and related devices are thoroughly described elsewhere in this Special Issue.

**A. Examples of Lossy Structures**

Several structures employing microwave absorbers are illustrated schematically in Fig. 8. Fig. 8(a) is a TWT sever, placed behind the slow-wave helix to provide isolation between the large output signal at the downstream end of the helix and the weak-signal area upstream [21]. The lossy material is typically arranged in the shape of a long, thin blocks or strips placed at various azimuthal locations (often connected to the structure that supports the helix). In the absence of the sever, oscillation would occur due to feedback or backward-wave interactions. The power handling requirement on the absorber can be a significant fraction (several percent) of the TWT output power capability. In many lower power helix TWT’s, sections of the helix supports are given a lossy conductive coating, consisting of an iron-based alloy or a carbonaceous material, instead of including a separate slab of lossy dielectric. For the suppression of backward-wave oscillations near the high frequency end of the bandwidth, helix TWT’s sometimes combine absorbing material with a resonant metal structure that is microprinted along the supports [27]. Large, high gain TWT’s often have two or three severs of various kinds placed along the length of the slow-wave structure.

Two schemes for loading TM modes in klystron or klystrode drift tubes are shown in Fig. 8(b) and (c). In Fig. 8(b), an annular cylinder of absorber lies behind a closely wound spiral of wire that defines the drift tube,
Unfortunately, rotating electron beams can be highly unstable when inadvertent cavities are formed by transitions in the beam tunnel wall and when reflections from the output window occur. The overmoded drift tubes and cavities employed in high-power gyrokystrons often trigger cavity-type oscillations and backward-wave instabilities which can completely overwhelm amplifier operation. Microwave absorbing materials are therefore of critical importance in gyrokystrons [29]–[33]. They can provide high attenuation and low quality factors to spurious drift tube modes, and they can stabilize beam-disrupting instabilities that occur in the magnetic compression region between the electron gun and the input cavity. When used in input and buncher cavities, they can produce very low quality factors (50–300) in the operating mode without affecting mode purity, and they can simultaneously raise the start oscillation currents of all competing modes.

Overmoded drift tubes in gyrokystrons can be loaded by the schemes previously described in Fig. 8(b) and (c) or by the nonresonant method shown in Fig. 8(d). Often, the fundamental TE\(_{11}\) mode in circular waveguide is the most troublesome mode to load. For example, the spiral wire structure produces very little attenuation to the TE\(_{11}\) mode. This may seem surprising since the TE\(_{11}\) mode has nonzero axial currents, which should escape past the helix and enter the dielectric. However, the pitch spacing typically used in this configuration is too small to allow a substantial amount of axial magnetic field (\(H_z\)) coupling. Typical attenuations are only a few decibels per meter at microwave frequencies, which in general will not provide sufficient loading for a high-power system. In contrast, the resonant slot configuration of Fig. 8(c) can provide very high attenuation over a limited bandwidth, provided that the slots are at least a half-wavelength (in the dielectric) long to allow coupling to (and outward radial propagation of) a mode with an \(H_z\) component inside the slot. The demands on the dielectric in this configuration were discussed above.

In the geometry of Fig. 8(d), a relatively thin (several millimeters radial thickness) lining of lossy dielectric provides moderately high attenuation over a very large bandwidth [30]. Many different modes can be simultaneously loaded by this method, and the loading is relatively insensitive to both the dielectric constant and the dimensions in comparison with the resonant case. In general, the dielectric should have high \(\tan\delta(>0.2)\) and low to moderate \(\varepsilon''(4-10)\) for broad response and to limit the creation of additional propagating modes. In some nonresonant designs, the inner surface of the dielectric is tapered or saw toothed to reduce reflections at the dielectric interface and improve the loading of modes near cutoff. In drift tube configurations where a large amount of surface is covered with dielectric, a slight dc conductivity in the dielectric is desirable. It helps bleed off charges deposited by beam scraping. Drift tube designs of this type have been successfully employed in a 9.85-GHz, three-cavity gyrokystron which produced 28-MW peak power for 1 \(\mu s\) [30], and a second harmonic, 19.7-GHz, two-cavity gyrokystron which produced 32-MW peak power for 0.9 \(\mu s\) [32]. A variation on this technique involves replacing the single layer of lossy material by a double layer of two different materials with vastly different dielectric properties. Such an arrangement can greatly increase the number of modes that can be effectively loaded. Double layer designs are being employed in ongoing efforts to produce 120–150 MW of peak output power at 17 GHz from a coaxial drift tube gyrokystron with 300-MW peak beam power [33].

Fig. 8(e) illustrates a method of loading a klystron or gyrokystron input or buncher cavity by placing a lossy dielectric inside the cavity. With this scheme, a very low operating-mode quality factor can be achieved, and many different lower or higher order modes can be simultaneously loaded. The resonant frequency and quality factor will depend strongly on the dielectric properties and dimensions. Therefore, the absorber for such an application should have dielectric properties insensitive to temperature, high dimensional accuracy, and reproducible dielectric properties. A low value of \(\varepsilon''\) helps reduce the sensitivity to dimensions. A lossy material that can be manufactured with a controllable value of \(\varepsilon''\) allows the quality factor to be adjusted during the design process. Once the associated value of \(\varepsilon''\) is known, the cavity dimensions can be adjusted to vary the resonant frequency with comparatively little effect on the \(Q\). Lossy dielectric can also be placed in the form of buttons on the wall of a cavity, as shown in Fig. 8(f). In this configuration, the dielectric causes minimal perturbation to the cavity electromagnetic fields. Furthermore, the spatially selective placement of dielectric can load certain modes at their high field locations without strongly affecting desirable modes.

B. Properties of Absorber Materials Relevant to Vacuum Electronic Devices

The discussions of the previous sections refer to a variety of desirable dielectric properties, depending on the type of lossy structure and its purpose. The primary type of dielectric absorber employed in the vacuum electronics industry is a composite composed of a high thermal conductivity, electrically insulating ceramic combined with lossy silicon carbide (SiC) [34]. Most typically, BeO is used as the electrically insulating base ceramic due to its high thermal conductivity of 250 Wm\(^{-1}\) K\(^{-1}\) [6]. SiC exhibits polytypism and can accommodate a substantial variety of impurities [35]. Although ultrapure, single-crystal SiC is a wide bandgap semiconducting material with low microwave loss (particularly those types referred to as 4H- and 6H-SiC), impure grades are highly lossy and suitable for use in composite absorbers. The standard Acheson process for making raw SiC involves reacting SiO\(_2\) and carbon in an electric furnace [35]. The resulting SiC contains considerable carbon and nitrogen impurities which lead to substantial electrical conductivity. Mixtures of BeO and SiC, both with grain sizes of about 5 \(\mu m\), are mixed together and subjected to hot uniaxial pressing at about 1800°C and 14 MPa (2000 psi) for several hours [34]. Although any composition can be achieved, the most common mixtures used in vacuum electronic devices are 60% BeO-40% SiC.
and 80% BeO-20% SiC (all by weight percentages). The resulting bulk cylindrical forms are diamond cut and ground to the desired shape.

The thermal conductivities of the composites are considerably lower than that of pure BeO. For example, the 60% BeO-40% SiC material has a thermal conductivity of 160 Wm$^{-1}$ K$^{-1}$, which is 64% of the value for pure BeO. The primary cause of this degradation in the BeO materials is the relatively low thermal conductivity of the impure SiC, which is only about 40 Wm$^{-1}$ K$^{-1}$. Although grades of SiC with much higher thermal conductivity can be synthesized, they do not have the required loss to perform adequately in microwave absorber applications. In any case, the 160 Wm$^{-1}$ K$^{-1}$ thermal conductivity for the BeO–SiC system is generally adequate for high average power applications, such as using the absorbing material to load the operating mode of a cavity. To take full advantage of the thermal conductivity, the ceramics should be brazed into the metallic microwave circuits to form a good thermal contact. This can be achieved with active metal brazing technology, in which titanium-copper or titanium-copper-silver alloys are sandwiched between the composite ceramic and the metal surface and heated in a high vacuum. The metal structure onto which the ceramic is brazed needs to be a ductile material such as oxygen free, electrolytic copper, to absorb stresses caused by differential thermal expansion.

The dielectric properties of a single 80% BeO-20% SiC sample as a function of frequency are plotted in Fig. 9. There are considerable sample-to-sample and lot-to-lot variations in the dielectric properties of these materials. From 8–12 GHz, the typical complex dielectric constant of 80% BeO-20% SiC is close to 17-j20. Raising the amount of SiC increases both the real and imaginary parts of the dielectric constant. For 60% BeO-40% SiC, the 10 GHz dielectric constant is about 42-j19.

To achieve lower dielectric constants, a second type of microwave absorber that consists of a mixture of glassy carbon in an aluminum silicate base can be employed [36]. These absorbers are produced by impregnating a slightly porous (5%) aluminum silicate machinable ceramic with a carbohydrate solution and converting it to carbon with a combination of CO$_2$ and H$_2$ firings. The thermal conductivity of this material is only about 5 Wm$^{-1}$ K$^{-1}$. The porous nature of the resulting ceramic requires rigorous bake-out procedures to allow operation in high vacuum systems. If desired, a similar material can also be manufactured from powdered glassy carbon and aluminum silicate and pressed to full density in a hydrogen atmosphere, eliminating the potential outgassing problems. The dielectric properties as a function of frequency for the porous version of the material are also plotted in Fig. 9. The value at 10 GHz is typically 60-j1.2. A carbon concentration of only 0.43% by weight produces this loss in the porous ceramic infusion process, while about 10–15% carbon is required if the powder pressing procedure is employed.

The two classes of materials, ceramic-SiC and carbon-impregnated aluminum silicate, each have specific advantages. The ceramic-SiC composites exhibit much higher mechanical strength and thermal conductivity (particularly with BeO as the base ceramic), higher electrical breakdown strength, the possibility of very high dielectric loss, and vastly lower outgassing rates. Some of these advantages are due to the intrinsic properties of the constituents, and others are due to the lack of porosity. These types of absorbers are the only choice for applications that require absorption of nontrivial amounts of electromagnetic power, and they are also desirable when a high dielectric constant is required. BeO can be replaced by aluminum nitride (AlN) to form a nontoxic absorber system. However, at present, the thermal conductivities of AlN composites are about a factor of three lower than those of BeO–SiC, although the dielectric properties are similar. The carbon-impregnated aluminum silicate materials exhibit a considerably lower $\varepsilon'$ for a given value of $\tan \delta$, which is desirable in several of the drift tube applications discussed previously. The low thermal conductivity is tolerable when the purpose of the absorber is to prevent oscillations from occurring in normally field-free regions of the structure. In the absence of oscillations, there is not any average power to absorb, and heating is not a problem. Fully dense versions of this absorber system do not suffer from outgassing problems. In the most general analysis, one can conclude that both types of absorber are useful in different areas of a sophisticated vacuum electronic device.

IV. COOLING TECHNIQUES FOR HIGH-HEAT-FLUX METAL STRUCTURES

Metallic surfaces subjected to heating in vacuum electronic devices include beam collectors, RF circuits, and RF cavity walls. In the case of beam collectors, the heat source is from residual kinetic energy present in the electron beam after it exits the microwave circuit region of the device. The electrons collide with the metallic surface of the collector and deposit the heat load in the near-surface regions. The deposited heat diffuses through the bulk of the collector metal by thermal conduction, where it must be removed by forced convection with a cooling fluid or some other scheme. The coolant of choice is water, due to its high

![Fig. 9. Measured frequency variation in the complex dielectric properties of 80%BeO-20%SiC and carbon impregnated aluminum silicate (Al$_2$O$_3$-SiO$_2$-C) microwave absorbers.](image-url)
heat capacity and relatively high boiling point, although water-glycol mixtures are sometimes used. The maximum amount of thermal power density that can be removed by conventional cooling schemes involving macroscopic cooling channel dimensions is in the 1–2-kW/cm² range.

Similar heat transfer considerations apply to the metal surfaces of the microwave circuit regions, such as the walls of microwave cavities and waveguides. In this case, the heating comes from ohmic losses associated with RF currents created by the electromagnetic fields within the structures. As in the case of beam collectors, flowing fluids are generally used to remove the absorbed power.

The problem of heat removal in metal structures is often a limiting factor in high-power, high-frequency devices. Thus, an obvious way to increase the average power capability in vacuum electronic microwave amplifier circuits is to incorporate schemes that can remove heat fluxes well above the 1–2-kW/cm² range. Two exciting materials-based technologies that can accomplish this are flow boiling at modest pressures and porous metal cooling. Flow boiling involves allowing the fluid in cooling channels to boil in a controlled manner, thus combining the advantages of normal convective cooling with the cooling effect associated with vaporization. In the porous metal technique, the cooling fluid passes through heat transfer regions that are filled with an open porosity, partially sintered metal matrix instead of ordinary smooth-walled cooling channels. In this section, the factors which limit conventional liquid cooling channel heat transfer will be presented, followed by a discussion of flow boiling. Following this, the physics and technology of the porous metal cooling scheme will be described.

A. The Limitations of Conventional Liquid Cooling

A diagram of a conventional cooling scheme based on channels containing flowing cooling liquid is shown in Fig. 10. The incident heat flux impinges on the surface at the bottom of the diagram and diffuses through the metal toward the cooling tubes. Heat is transferred to the liquid, raising its temperature, and this absorbed heat is carried away by the flow. The average temperature of the fluid, \( T_b \), (also known as the bulk fluid temperature) as a function of distance down the tube, \( x \), is determined by energy conservation and is given by

\[
T_b(x) = T_i + \frac{q_0^p \pi D x}{\dot{m} c_p} \tag{9}
\]

where \( T_i \) is the inlet temperature, \( q_0^p \) is the heat flux on the tube surface (power/area), \( D \) is the tube diameter, \( \dot{m} \) is the fluid mass flow rate, and \( c_p \) is the specific heat of the fluid. In real fluids, the heat transfer is limited by the viscosity of the fluid and the thermal conductivity, so there is a strong radial temperature gradient across the fluid. Mathematically, this is equivalent to a junction thermal resistivity between the bulk fluid temperature and the metal surface temperature, \( T_s \). The temperature of the fluid immediately adjacent to the metal is also equal to \( T_s \). In practical heat transfer situations, it is the rise in surface and adjacent fluid temperature (rather than the bulk fluid temperature) which usually limits the maximum amount of heat flux that can be absorbed.

The functional form of the radial thermal profile and the overall thermal gradient across the fluid depend on whether the flow is laminar or turbulent, the details of the geometry, and the boundary conditions ascribed to the walls of the tube. Numerous references describing theoretical and experimental correlations between the process variables and the heat transfer coefficient can be found in the literature [37, 38], so we will not cover the details here. Instead, we will summarize by stating that an effective heat transfer coefficient, \( h \) (MKS units Wm⁻² K⁻¹) relates the difference between the wall temperature and the bulk fluid temperature to the heat flux according to

\[
T_w(x) = T_b(x) + \frac{q_0^p}{h} \tag{10}
\]

The heat transfer coefficient is related to a dimensionless quantity known as the Nusselt number, \( N_u \), according to

\[
h = \frac{N_u \kappa}{D} \tag{11}
\]

where \( \kappa \) is the fluid thermal conductivity. The Nusselt number is the ratio of convection for a fluid in motion to the thermal conduction through a motionless fluid layer. Calculations of convective heat transfer in various geometries and flow conditions available in the literature are always expressed in terms of Nusselt numbers.

For the case of turbulent flow in a tube, the Nusselt number is approximately given by the Petukhov-Kirillov [39] correlation

\[
N_u = \frac{(f/2)R_e P_r}{1.07 + 12.7 \sqrt{f/2} \left( \frac{P_r}{R_e} \right)^{2/3} - 1} \tag{12}
\]

In this equation \( R_e = u D \rho / \mu \) is the Reynolds number, \( P_r = \mu c_p / \kappa \) is known as the Prandtl number, \( u \) is the fluid flow velocity, \( \rho \) is the mass density, \( \mu \) is the viscosity, and \( f \) is a friction factor approximated by

\[
f = (1.58 \ln R_e - 3.28)^{-2} \tag{13}
\]

For flow in a tube, a Reynolds number above \( 10^4 \) is considered fully turbulent.
C will cause boiling. Pushing past C, but the peak is the heat flux, C. In much the same manner, one must resort to geometrical tricks to distribute the heat from the receiving surface to several cooling tubes in a manner that reduces the heat flux into each tube. This is shown in the lower diagram of Fig. 10. The thermal resistance of the metal between each row of tubes can be considerably less than the resistance associated with heat transfer to the coolant. Careful design with finite element thermal analysis codes can ensure that the temperature gradient between the first row of tubes and the second is sufficient to force some heat through the metal toward the second row, without overheating the coolant in the first row (and so forth for subsequent rows). This method is used in high power electron beam collectors and microwave cavities. Since most vacuum electronic device structures such as cavities have a cylindrical symmetry, another option is to simply allow the heat to diffuse some distance radially (to lower the effective heat flux as 1/r) before it reaches the cooling tubes. This is particularly useful in millimeter-wave devices where the high heat flux is confined to a very small physical area. The downside of any of these techniques is that the heat-receiving surface will run considerably hotter than it would if the power density was directly removed at its full magnitude. At some point, the temperature of the heated surfaces will become sufficiently hot to cause failure by any one of several mechanisms: melting; vacuum outgassing; dimensional distortions due to thermal expansion; or mechanical stresses associated with high thermal gradients.

B. Cooling Schemes Involving Boiling

Rather than simply removing heat by warming the cooling liquid, another option is to allow the cooling fluid to boil. For a liquid such as water, which has a high heat of vaporization, a considerable increase in net heat removal is possible. It takes 419 J of energy to raise 1 g of water from 0 to 100°C, but to boil this same quantity requires 2256 J. But just as in single phase cooling, the limiting factor is not the ultimate energy removal capability of the fluid (through rise in average fluid temperature and boiling), but rather the transport of heat from the wall to the main body of the fluid. Referring back to the cooling tube example and Fig. 11, for 200 W/cm² and 5-m/s water velocity, the rise in bulk fluid temperature is only 3.8°C, but the peak wall temperature rise is 52°C. In much the same manner, boiling only involves a small amount of liquid near the heated surface; once this fluid turns to gas (i.e., vapor) additional cool liquid must flow in to replace it and the hot gas bubble must be allowed to escape. It is this mechanical transport which limits the heat removal.

For a simple horizontal, heated surface in a container of fluid, boiling heat transfer can be roughly described by equations such as the Rohsenow [40] correlation

\[ \dot{q}_b'' = a(T_a - T_{sat})^b \]  

(14)

where \( \dot{q}_b'' \) is the heat flux, \( a \) and \( b \) are numbers which depend on the fluid and surface properties, \( T_a \) is the surface temperature, and \( T_{sat} \) is the boiling temperature. For water at 1 atm pressure on a copper surface, \( T_{sat} = 100°C \), \( a = 0.0125 \), and \( b = 3.0 \) when \( \dot{q}_b'' \) is measured in W/cm² [37]. Equation (14) describes a condition known as nucleate pool boiling, in which individual bubbles form and float away from the surface. There is a limit to the heat flux that can be accommodated; this quantity is known as the critical heat flux [41]. At this level, the gas bubbles cannot depart quickly enough to allow fresh fluid to reach the surface, resulting in the formation of a continuous film of gas between the metal surface and the fluid. Since the heat transfer through gas is very poor, the surface temperature for a given heat flux under these “film boiling” conditions is dramatically higher than for nucleate boiling. The surface temperature will suddenly rise as the critical heat flux is exceeded. For example, the critical heat flux for water at 1 atm is only about 100 W/cm², corresponding to a 120°C surface temperature for nucleate boiling. For film boiling,
the temperature at the same heat flux will be about 600°C, including the effects of radiation cooling through the vapor film. The surface will quickly melt if additional increases in the heat flux are attempted. The critical heat flux can be raised by increasing the operating pressure. However, even at 100 atm the value is only 380 W/cm² [41], which is not very high considering the trouble associated with such large pressures. Enhancements in surface roughness, which are useful for improving low heat flux nucleate boiling transfer, have little effect on the critical heat flux.

However, dramatic increases in the critical heat flux can be achieved by combining forced fluid flow with nucleate boiling. In this manner, the gas bubbles can be forced to move away from the surface and new fluid can be delivered in a much more rapid manner than that achievable from the buoyant convection associated with pool boiling. In addition, the normal heat removal processes associated with single-phase forced convection simultaneously apply if the bulk fluid is subcooled below the saturation boiling temperature prior to entry into the cooling tube. With subcooling and turbulent flow, the hot gas bubbles can move into cooler regions of the flow and collapse, which releases their latent heat into the bulk of the fluid. An approximate formula [42] for the critical heat flux during flow boiling is

$$q''_{\text{max}} = 110 \left(1 + 2.0 \sqrt{u} t^{1/3}\right) + 7.7(T_{\text{sat}} - T_0)\left(1 + 1.4 t^{2/3}\right)$$

(15)

where the heat flux is in W/cm², $u$ is the flow velocity in m/s, and the temperatures are in °C.

Fig. 12 displays a plot of the critical flux as a function of velocity for various amounts of subcooling. If desired, the subcooling can be greater than 100°C if pressures above 1 atm are used. Comparing these power densities to the several hundred W/cm² values associated with the curves in Fig. 11 demonstrates the obvious improvement afforded by flow boiling. Although this plot is most valid for external flow over a heated plate, similar results can be achieved for internal flow in tubes. The peak heat transfer coefficients in any type of flow boiling can be 20–50 times greater than those of single phase forced convection, and the removal of 3.5 kW/cm² using this technique has been reported [43]. Most boiler systems for fossil-fuel power plants and nuclear reactors employ advanced flow boiling techniques. In a related technique, known as liquid jet cooling [44], submerged jets of liquid impinge upon the backside of the heated metal surface. The violent convection occurring where the jet contacts the wall greatly aids in heat transfer by delaying the onset of film boiling. In some experiments with this technique, power densities in excess of 10 kW/cm² have been removed from a surface heated by a plasma torch [44].

Flow boiling and closely related techniques are used in certain advanced gyrotron oscillators operating in the 1-MW continuous output power regime, at frequencies from 100 to 170 GHz. Such devices are used for electron-cyclotron resonance heating of magnetic fusion plasmas.

In these gyrotrons, the output cavity surface typically sustains a steady-state 2-kW/cm² heat flux [15], [45]. The total surface area of the output cavity is usually in the range of 15–30 cm², so the total amount of heat to be removed is substantial and the high flux is not just due to some geometrical singularity in a localized region of the cavity. Inner cavity wall temperatures have been kept below approximately 250°C using subcooling. Liquid jet cooling at 100 m/s velocity has been successfully applied to the problem of cooling the electron beam collection anodes of X-ray vacuum tubes [46], which are used for advanced materials processing applications.

C. Porous Metal Cooling

A relatively new cooling technique uses a porous metal medium to accomplish the transfer of heat from the hot surface to a fluid [47]. One class of porous metal heat exchanger employs a single phase (such as a liquid) which is pumped through the medium. A diagram of this type of heat exchanger is shown in Fig. 13. Fluid typically enters through holes, moves through the thermally conducting, porous medium parallel to the rear face of the heated surface, and exits through collection slots. The porous medium is made from partially sintered metal particles, in which the internal pore spaces are connected to the outside surfaces (known as open porosity). The porous layer must be intimately bonded to the heated surface, which is typically referred to as the faceplate, and to the coolant manifold plate.

A porous metal heat exchanger operates by a combination of thermal conduction between the joined particles of the
porous matrix and convection into the flowing liquid. The porous medium greatly increases the surface area available for convective cooling. In some sense, it can be viewed as a random-structured, three-dimensional extension of the multicooling tube concept of Fig. 10. A large heat flux arriving at the faceplate gets distributed over the internal surface area of the porosity, keeping the heat flux (and required local heat transfer coefficient) within the limits of normal liquid cooling. However, there is a large pressure drop associated with pumping liquids through the porous metal, which is why numerous coolant inlet and exit holes are required. The heat flux capability $q''$ of a single phase porous heat exchanger can be estimated using the design equation

$$q'' = \left( ph_t + \sqrt{h_t \kappa_w S_p} \right) \Delta T$$

where $p$ is the porosity ($0 \leq p \leq 1$), $h_t$ is the local particle to fluid convective heat transfer coefficient, $\kappa_w$ is the effective thermal conductivity of the porous material (also known as the wick), $S_p$ is the surface area of the porous medium ($\text{m}^2$ per $\text{m}^3$ of material), and $\Delta T$ is the wall-to-fluid temperature drop [47]. Equation (16) assumes a semi-infinite wick thickness normal to the faceplate. The wick thermal conductivity is approximately given by $(1 - p)^3$ times the metal thermal conductivity, while the surface area can be estimated by

$$S_p = \frac{6(1 - p)}{D_m}$$

where $D_m$ is the metal particle diameter [48]. Due to geometric uncertainties, it is better to measure both of these quantities experimentally.

Properties of a typical sintered copper wick reported in the literature [49] are $D_m = 70 \mu\text{m}$, $p = 0.4$, $\kappa_w = 60 \text{ Wm}^{-1} \text{K}^{-1}$, and $S_p = 5 \times 10^5 \text{ m}^{-1}$. The local heat transfer coefficient can be estimated from the Kar–Dybbbs [50] correlation for the Nusselt number

$$N_u = I_p^{1/3} \left( 0.4 \times 10^{-2} I_p^{1/3} \right)$$

and (11). In the computation of $h_t$ using (11) and the Reynolds number, the value of $D$ should be set equal to the mean pore diameter. In this example wick, a typical value of $h_t$ for a water coolant is $5 \times 10^5 \text{ Wm}^{-2} \text{K}^{-1}$, but this number will vary depending on the flow velocity in the pores. In Fig. 14, a plot of fluid temperature rise in this example wick as a function of liquid flow velocity through the pores is shown for various power densities. This figure can be directly compared to Fig. 11. Very reasonable temperature rises are obtained even at high power levels.

Porous metal cooling techniques have been applied in Russia to the problem of cooling gyrotron cavities, and power densities above 3 kW/cm$^2$ have been successfully managed [51]. More recent experiments in the United States involving porous metal cooling for gyrotron cavities and beam collectors have produced promising results. A test component fabricated for this purpose, consisting of a water-cooled, sintered copper wick in conjunction with a dispersion-strengthened copper faceplate, was able to repeatedly absorb 6 kW/cm$^2$ in 70-s pulses without any signs of failure [49]. Upon further testing, 7.4 kW/cm$^2$ was absorbed for 20 s before failure occurred when an uncooled portion of the test article was inadvertently heated [49]. The heat flux for these experiments was produced by an electron beam heating test facility, which provides an accurate representation of the conditions present in commercial vacuum power tubes.

At present, when water is used as a coolant, very high velocity (>20 m/s) flow boiling (particularly with submerged liquid jet impingement) and porous metal cooling have comparable capabilities. Both techniques have shown the ability to repeatedly absorb heat fluxes well in excess of 3 kW/cm$^2$ in test components and prototype vacuum electronic devices, with performances reaching the 7.5–10-kW/cm$^2$ range in short duration tests [44], [47]. However, since the technology of porous metal cooling is still in a relatively early stage, it is difficult to predict the ultimate limits of its capability. Improvements in theoretical modeling, as well as the use of tailored-microstructure wicks or wicks made from composite materials, might lead to additional advancements.

One type of porous metal cooling scheme that does not have a conventional technology counterpart is the heat pipe [47]. Heat pipes use passive two-phase heat transfer in a sealed container. Working fluid boils in a porous metal wick located in the area exposed to a heat flux, travels as vapor to cooler regions of the structure through unimpeded internal channels, and releases its heat through condensation at the far end of the structure. Capillary forces draw the condensate back through the porous wick to the heated region, forming a closed-loop system without the need for external pumping. This technology is being applied to a variety of electronic cooling applications, including TWT’s. According to manufacturers’ literature [52], average power production in an octave bandwidth TWT was increased from 1.3 to 2.6 kW using integral heat pipes imbedded in the housing. Because heat pipes operate without gravity, they are regularly used in space TWT’s designed for communications satellites. Successful heat pipe applications
in TWT’s have included beam collector cooling, cooling of the RF interaction structure vacuum jacket, and the cooling of solenoid magnets [52]. New applications of porous metal cooling and heat pipes to all types of vacuum electronic devices will undoubtedly be explored as power and bandwidth requirements rise.

V. Applications of Pyrolytic Graphite

Pyrolytic graphite is a synthetic carbon-based material which is formed by the thermal cracking of hydrocarbon gases. It is a mechanically strong, vacuum compatible material that exhibits a high degree of anisotropy in its physical properties. This anisotropy, coupled with other desirable properties, such as low secondary electron emission, make pyrolytic graphite a useful material in vacuum electronic devices. In the following subsections, we will describe the manufacture and physical properties of pyrolytic graphite, followed by a discussion of applications such as beam collectors and cathode modulation grids.

A. Manufacture, Structure, and Properties of Pyrolytic Graphite

Pyrolytic graphite is produced when a hydrocarbon gas comes into contact with a hot surface and decomposes [53]. Typical choices for the hydrocarbon are ordinary natural gas or purified methane. The substrate onto which the gas will decompose must resist the high temperatures and carbonaceous atmospheres, while presenting a suitably smooth surface for uniform growth conditions. Only refractory metals, certain metal carbides such as SiC, and ordinary polycrystalline graphite are acceptable substrates; the latter is most typically selected for reasons of cost. Since the pyrolytic graphite structure will grow onto the substrate, the substrate must be machined with the appropriate dimensions for the desired final product shape. Typical conditions for graphite deposition are a substrate temperature in the range of 1700–2250°C and a hydrocarbon gas pressure of 1–50 torr. The substrate is heated by either radiant heat from resistive elements or by the induction heating of a graphite susceptor. The thickness of the deposited pyrolytic graphite is controlled by the process variables (temperature, pressure) and the total deposition time. Pyrolytic graphite is essentially pore free and is relatively easy to de-gas for vacuum operation.

In order to understand the physical nature of pyrolytic graphite, some discussion of ordinary graphite is required [54]. A diagram of the atomic arrangement in single crystal graphite is shown in Fig. 15. Graphite consists of stacked layers of carbon atoms. Within each layer (the so-called AB plane), each carbon atom is covalently bonded to its three nearest neighbors with 1.42-Å spacing; these bonds are very strong. The layers are stacked upon each other (the stacking is in the C direction) so that the carbon atoms in every other layer (6.71-Å spacing) have the same orientation with respect to the coordinate axes, while the alternate layers are rotated in the AB plane by 60°. Only very weak Van der Waals bonding exists between adjacent planes in the C direction (which are spaced by 3.35 Å).

The different types of bonds that exist in graphite cause a high degree of anisotropic behavior. Within the AB plane, the structure has excellent thermal and electrical conductivity. The close mechanical coupling and high bond energy between the adjacent AB plane atoms results in a very stiff material. Young’s modulus in the AB plane direction is 940 GPa (second only to that of diamond at 1220 GPa). This stiffness, coupled with the low atomic weight of carbon, creates the high thermal conductivity. The carbon–carbon bonds within the AB plane consist of one sigma-bonding molecular orbital and one pi-bonding molecular orbital. Electrical conductivity results from the fact that the pi-bonded electrons are delocalized, much like the conduction band electrons in a metal. In response to an applied electrical field, these delocalized pi-electrons easily migrate from atom to atom within the AB plane. In contrast, the C direction bonding is so weak that only negligible thermal and electrical conductivity can occur in this direction.

Graphite produced by pyrolysis has the AB plane layers oriented roughly parallel to the deposition substrate surface (C-direction is perpendicular to the surface). When the pyrolytic graphite is produced at intermediate temperatures of approximately 1800–2000°C, the degree of ordering in the AB plane approaches 100% (as in single crystal graphite). However, the stacking of layers in the C direction is highly random in both spacing and three-dimensional relative angular orientation. The layers can be considered as only being approximately parallel in some average sense. Thus, pyrolytic graphite produced at these intermediate temperatures is even more anisotropic than conventional single crystal graphite, due to the greater degree of disorder.
in the $C$ direction. The average $C$ direction spacing is 3.45 Å for pyrolytic graphite produced at 2000°C, compared to 3.35 Å in single crystal graphite. As the deposition temperature is raised, or as material initially deposited at lower temperature is annealed to higher temperatures, the $C$ lattice spacing gradually decreases toward the single crystal value. By the time 2900°C is reached, the deposited material is nearly identical to single crystal graphite. The grain size and surface roughness of the pyrolytic graphite are also strong functions of the deposition temperature. Materials formed at 1800°C have 50–200 Å grain sizes, while those created or annealed at 2900°C have micrometer-sized grains.

The low porosity, low vapor pressure, low secondary electron emission characteristics, and high temperature capabilities of pyrolytic graphite make this material very attractive for demanding vacuum electronics applications [55]. The anisotropies of the thermal conductivity and thermal expansion play a particularly useful role in fabricating unique electron device components. A plot of the variation in thermal conductivity as a function of temperature is shown in Fig. 16 [53]. At room temperature, the thermal conductivity in the AB plane is slightly better than that of copper, while the $C$ axis thermal conductivity is similar to that of fused quartz. This translates into a thermal anisotropy of $1.1 \times 10^5$. As the temperature increases, the thermal conductivity in the AB plane drops considerably, although at 400°C the value is still comparable to refractory metals such as tungsten. The $C$ axis thermal conductivity exhibits only small variations, so the anisotropic nature of the material remains substantial throughout the measured temperature range. The thermal expansion coefficient for pyrolytic graphite at temperatures above 400°C is $1.8 \times 10^{-6}$ in the AB plane and $23.4 \times 10^{-6}$ along the $C$ axis. At lower temperatures, the $C$ axis expansion coefficient retains its high temperature value, but the AB coefficient quickly drops to zero between 400 and 200°C and is negative below 200°C. As a result of this varying expansion coefficient (and low overall numerical magnitude), the AB dimensions of a pyrolytic graphite component do not experience a substantial overall change throughout the 0 to 400°C range.

### B. Pyrolytic Graphite Collector Electrodes

Vacuum electronic devices convert the dc energy of an electron beam into useful electromagnetic energy within an interaction structure. Even in highly efficient interaction processes, a significant fraction of the initial kinetic energy remains in the electron beam and must be dissipated as heat when the beam strikes a collector electrode. As we have seen in the section on cooling technologies, removal of this heat can be a challenging problem in high average power devices. Even if the thermal problems can be managed, this residual beam energy often cannot be ignored if high overall system electrical efficiency is to be achieved. An example is an octave-bandwidth TWT, which typically has an RF conversion efficiency of only 15%. The energy of the residual beam can be extracted and effectively returned to the power supply by means of a depressed collector [56]. In this scheme, the collector is biased negatively with respect to the RF circuit so that the electron velocity is decreased (converted into potential energy) by the local dc electric field before it strikes the collector. Not only will this result in improved total system efficiency, but the thermal loading of the collector is decreased. Multistage depressed collectors, each operating at a specific negative voltage, can be used to effectively segregate and collect beams with a substantial energy spread. The ideal collector material should have high thermal conductivity, good vacuum characteristics during electron bombardment and associated heating, and very low secondary electron emission. Secondary electron emission, which is the ratio of re-emitted electrons to impinging electrons, must be low in a depressed collector to attain high overall efficiency. Otherwise, the secondary electron current will reach other electrodes, resulting in a net current (and power drain) between the various electrodes of the collector.

Pyrolytic graphite has a number of desirable properties for application in multistage depressed collectors [55], [57]. Compared to oxygen-free-high-conductivity (OFHC) copper, it has a much higher thermal emissivity and elevated temperature capability. As with other graphites, such as isotropic polycrystalline graphite, it has a low secondary emission ratio due to the low atomic weight of carbon. This allows electrons to penetrate more deeply into the material. Accordingly, a greater fraction of the low-energy electrons released from the collector’s atoms by the primary electron impact cannot penetrate backward through the material and escape. The specific advantages of pyrolytic graphite over isotropic graphite arise from the exceptionally low secondary emission from surfaces perpendicular to the AB plane (e.g., the AC or BC planes), the high thermal conductivity in the AB plane (comparable to OFHC copper), and the absence of porosity to trap gases.

A typical pyrolytic graphite collector is roughly in the shape of a hollow cylinder. The electron beam impinges mainly on the inner diameter, and the outer diameter is brazed with active metal techniques to annular alumina insulators which electrically isolate the electrodes and hold them in proper position within the vacuum jacket. Some-
times a segmented metal spacer is placed between the graphite and the alumina to prevent stress buildup. The pyrolytic graphite is oriented so that the AB planes are perpendicular to the z-axis of the cylinder. Thus, the thermal energy can readily flow radially outward toward the vacuum jacket, while at the same time the inner surface of the cylinder consists of surfaces parallel to the C axis, which have low secondary emission. This is particularly true if the material has been roughened by ion texturing [58]. Under these conditions, the maximum secondary yield is 0.22 or smaller, compared to 0.6 for untreated isotropic graphite and 0.95 for OFHC copper.

TWT’s utilizing multistage depressed collectors composed of pyrolytic graphite have been constructed and tested by Ramins, Ebihara, and other colleagues at NASA [59]. TWT’s from several manufacturers were successfully modified by adding custom manufactured depressed collector assemblies. One tube was designed to produce a nominal 500-W continuous wave output over the 4.8–9.6-GHz frequency range, while a second tube was designed to produce a nominal 840-W from 2.5–5.5 GHz. The high vacuum compatibility of pyrolytic graphite was demonstrated by the $1 \times 10^{-10}$ torr pressure attained in both of these tubes after a standard 450°C bakeout. The 4.8–9.6-GHz tube achieved a 42.1% overall TWT system efficiency with a five-stage collector, compared to 11.9% without the collector. The lower frequency tube was tested with a three- and four-stage collector, achieving 44.7% and 46% system efficiencies, respectively. In this case, the efficiency without the depressed collectors was 21%. The pyrolytic graphite collectors allowed between 5 and 8% additional system efficiency compared to standard OFHC depressed collector electrodes. This additional improvement in efficiency is critical for power-consumption-sensitive applications such as satellites. These lower frequency results led to a successful effort to develop a 20-GHz frequency-range TWT employing ion-textured pyrolytic graphite depressed collectors [60]. Multistage depressed collectors employing pyrolytic graphite have been utilized in selected high-power TWT’s manufactured for broadcasting satellites [55], [61].

More widespread commercial application of pyrolytic graphite to collectors (as opposed to the more common isotropic graphite and carbon-coated copper collectors) will depend on the development of improved manufacturing and processing techniques to limit residual thermal stresses that can occur in the material. Such stresses, particularly in structures with a large amount of curvature and heavy thermal cycling, can occasionally cause graphite layers to flake off into the vacuum envelope and trigger arcing. One related type of chemically synthesized graphite with improved thermomechanical stability consists of oriented pyrolytic graphite fibers embedded into a polycrystalline graphite matrix. These high thermal conductivity, highly anisotropic carbon-carbon composites [62], [63] have proven useful in rocket nozzle inserts [64], which are subjected to severe thermal gradients and shocks. It seems reasonable that such a composite might be applicable in next-generation collector designs.

C. Cathode Modulation Grids Fabricated from Pyrolytic Graphite

Gated emission vacuum tubes occupy a substantial market share in ground-based VHF and UHF television broadcast service. Conventional triodes and tetrodes dominate at the lower frequencies. One particular higher frequency (300 MHz–1 GHz) device, known as the klystrode, operates by heavily modulating the current emitted by a thermionic cathode at the operating frequency [65]. A grid structure situated just above the cathode accomplishes this modulation. This “prebunched” beam travels down a short drift tube, which is cut off to waves at the frequency of interest. After emerging from the drift tube, the beam enters an output cavity in which the ac space charge modulation on the beam excites electromagnetic fields. These fields are extracted from the cavity through an aperture. The klystrode is essentially a combination of a klystron output cavity and drift tube with a triode-style cathode-modulation grid assembly (explaining the origin of the trade name). It boasts an efficiency as high as 80% without the use of a depressed collector.

A challenging problem for high-frequency, high-power devices of this class is fabrication of the grid structure [66]. The grid structure must be very close to the cathode surface to avoid transit time effects, and it must not structurally sag, expand, or make contact with the cathode at high temperatures. The solid portions of the grid must be narrow to avoid substantial beam interception, and the grid must have high thermal conductivity to remove heat from residual beam interception and from impinging infrared radiation from the thermionic cathode. Pyrolytic graphite is an ideal material for this application on the basis of its intrinsic material properties. When oriented so that the AB surface is parallel to the hot cathode, the direction of high thermal conductivity is in the radial direction. The low thermal expansion of the material, particularly in the AB direction, allows the thin grid structure to avoid buckling as the temperature changes. On the basis of room-temperature strength, a pyrolytic graphite grid structure can be made structurally thin and can accommodate a large fraction of its area being cut away to allow the electron beam to pass downstream. Unlike metals, the rigidity, the tensile strength, and the flexural strength of pyrolytic graphite actually increase as the temperature rises. Thus, a pyrolytic graphite grid structure will not sag or warp at the operating temperatures (typically 700–1000°C). Other desirable properties of pyrolytic graphite for grid applications include high thermal emissivity, which provides additional radiative cooling, and a low secondary electron yield.

Pyrolytic graphite grids are deposited on a substrate with the same contour of the cathode surface. The grid lattice is formed by laser machining the surface in an air environment [66]. In a 500-kW, 26-MHz tetrode, a pyrolytic graphite grid can provide twice the power dissipation of a conventional coated-molybdenum grid. A detailed study comparing the performance of pyrolytic graphite grids with conventional refractory metal grids...
VI. APPLICATIONS OF RARE-EARTH PERMANENT MAGNETS

For most applications, electron beams used in vacuum electronic devices must be magnetically confined to retain optimal shape and spatial position. Without confinement, the repulsive forces between electrons will cause the beam to spread, leading to radial or azimuthal asymmetries, decreases in beam-wave coupling efficiency, and, in the worst case, a catastrophic failure of the tube from beam interception on the walls. The challenge for the vacuum electronics designer is to develop magnetic focusing systems that adequately confine and guide the beam while conforming to overall system volume and weight restrictions. As the operating frequency increases, this challenge is increasingly difficult to meet since dimensions decrease, sensitivity to mechanical tolerances increases, and the magnetic focusing system must exert increasingly fine control over the electron beam. For example, at W-band frequencies (75 to 110 GHz), coupled-cavity TWT beam tunnels can be as small as 0.5 mm in diameter with beam diameters on the order of 0.25 mm. While solenoid electromagnets can supply adequate fields with the required spatial uniformity, the size and weight of the magnets, power supplies, and cooling systems are often prohibitive, particularly for air- and space-borne applications.

The properties of permanent magnet materials, particularly compounds based on rare-earth elements, have significantly advanced in the last two decades. The magnetic properties of the rare-earth materials far surpass those of ferrite and Alnico. With their high resistance to demagnetization, rare-earth permanent magnets can be fashioned into volumetrically efficient, high-field structures that can offer an attractive and viable alternative to electromagnets.

The relevant materials properties for permanent magnets used in vacuum electronic devices include the maximum energy product, \((BH)_{\text{max}}\), the coercivity, \(H_c\), the thermal stability, and the Curie temperature, \(T_C\). The maximum energy product (MKS units of Jm\(^{-3}\)) is a measure of the maximum energy density that can be stored in a given magnetic material. This quantity has important consequences for minimizing system volumes and weights since a permanent magnet operated at \((BH)_{\text{max}}\) will deliver a given amount of flux using the minimum amount of magnetic material. The coercivity (ampere-turns/m) is the amount of externally applied magnetic field necessary to reduce the magnetic flux density in a particular magnetic material to zero. For electron beam guiding applications, it is desirable to use magnetic materials with \(H_c\) as high as possible to avoid demagnetization by the self-fields of the beam or proximity to other magnetized materials. The thermal stability is a measure of the degree to which the magnetic properties change with temperature. In permanent magnet materials, these changes are classified as: “reversible” when the original properties are restored by simply returning the material to its initial temperature; “irreversible” when remagnetization is required to restore the original properties even after the material has been returned to its original temperature; or “structural” when there is a permanent change to the grain or crystallographic structure of the material. The Curie temperature is the temperature above which the elementary magnetic moments become randomized and the material reverts to weaker, paramagnetic behavior—practical maximum operating temperatures lie in the range of about 0.35\(T_C\) to 0.9\(T_C\), depending on the material and specific application.

A. Advances in Permanent Magnetic Materials

In a recent overview of the subject [69], Parker identifies three significant milestones in the history of permanent magnets. The first milestone dates back to the nineteenth century with the onset of widespread use of weak magnetic materials in devices such as compasses, magnetos, and meters. The second milestone occurred in the 1940’s with the development of permanent magnet materials, most notably alloys of aluminum-nickel-iron-cobalt (Alnico), that could favorably compete with electromagnets. The third milestone, and the one that is most significant to current and future vacuum electronic devices, is the development of rare-earth permanent magnets.

Permanent magnets made from alloys of rare-earth elements were first introduced in the 1960’s, with the first practical magnets appearing in 1970 [70]. These new materials represented a significant improvement over the best available materials of the time. Since the 1970’s, the continuing development of binary and, more recently, ternary compounds of rare-earth elements and transition metals has produced permanent magnetic materials with unprecedented volumetric efficiencies and resistances to demagnetization. Fig. 17 is a plot of some of the developmental highlights in high energy product materials since 1930. By the mid-1980’s, rare-earth permanent magnets had achieved a more than fivefold increase in \((BH)_{\text{max}}\) and a more than eightfold increase in coercivity compared with the best Alnico magnets. Table 4 summarizes the properties of some commercially available permanent magnetic materials. While the list is by no means exhaustive, the properties are representative of the major classes of permanent magnet materials (ferrites, Alnicos, and rare-earths) used in vacuum electronic amplifier design. The lanthanide...
rare-earth elements span atomic numbers 58 (cerium) to 71 (lutetium). Rare-earth permanent magnets are most commonly produced from either binary compounds of a rare-earth element with cobalt, or ternary compounds of a rare-earth element with iron and boron. Although impurities may be added to enhance or suppress particular properties, such as temperature stability, the best results to date have been achieved with the basic formulations of SmCo₅, Sm₂Co₁₇, and Nd₂Fe₁₄B. These compounds have a high degree of magnetocrystalline anisotropy (characteristic of the intrinsic material and enhanced by the choice of processing method) and are strongly ferromagnetic. Depending on the compound and method of processing, the observed high coercivity is explained by one of three theoretical models: nucleation (SmCo₅; sintered Nd₂Fe₁₄B); pinning (Sm₂Co₁₇); or single domain (hydrogenation, disproportionation, desorption and recombination (HDDR)-processed Nd₂Fe₁₄B). The particular methods of bulk material preparation, pressing, sintering or forming, and heat treatment contribute to the final magnetic behavior of the material. The reader is directed to appropriate textbooks [69], [72] for detailed discussions of the physics of these materials as well as the various fabrication and processing methods.

In general, the maximum operating temperature for rare-earth permanent magnets is about 0.5 \( T_C \), or 300–350°C for samarium cobalt and about 150°C for Nd–Fe–B. The reversible temperature coefficient for samarium cobalt is comparable to that of Alnico, 0.03% \( \frac{B_T}{\circ C} \) and 0.02% \( B_T/\circ C \), respectively; Nd–Fe–B is markedly poorer at 0.12% \( B_T/\circ C \). Materials can be compensated to achieve relatively flat temperature characteristics by altering their grain structures and crystallographic orientations through mechanical processing, heat treatment, and the introduction of impurities. However, temperature compensation is not without a price. For example, the introduction of an impurity such as gadolinium can improve the thermal stability of a rare-earth magnet but at the expense of reducing the residual magnetization. The choice of a particular magnet material is application specific, with tradeoffs made between residual magnetization, energy product, coercivity, temperature stability, and maximum operating temperature.

### B. Examples of Novel Applications of Rare-Earth Permanent Magnets in Linear Beam Vacuum Power Tubes

Rare-earth permanent magnets can provide bulk-reducing solutions to a wide variety of vacuum electronic devices, including linear beam devices such as TWT’s and klystrons, and fast-wave devices such as free-electron lasers and gyrotrons. For the purposes of illustration, the following sections will focus on applications of rare-earth permanent magnet technology to linear beam tubes. The designs and specific examples are drawn from the pioneering work of Leupold and his colleagues at the Army Research Laboratory.

In linear beam devices, the Brillouin field, \( B_{Br} \), is the minimum axial magnetic field that exactly balances the space charge and centrifugal forces within the beam and is related to the beam voltage, \( V_b \), beam current, \( I_b \), and radius, \( r_b \), by [73]

\[
B_{Br} = \frac{8.302 \times 10^{-4} \frac{1}{V_b^{1/4} I_b^{1/2}}}{r_b} \tag{19}
\]

where \( B_{Br} \) has units of Tesla. As the beam radius decreases, there will be a proportional increase in the magnetic field required to confine the beam. This situation is exacerbated at millimeter-wave frequencies where the beam radius can be very small, as illustrated in Fig. 18, where \( B_{Br} \) is plotted as a function of \( I_b \) for several beam voltages and radii. The Brillouin field is a minimum field; to reduce sensitivity to small fluctuations in beam parameters and to provide a greater restoring force to the beam, practical tube designs typically employ magnetic fields of up to three times \( B_{Br} \) in strength. The axial magnetic field range of 0.02 to 0.6 T is of interest for many linear beam device applications.

Magnetic beam confinement is typically achieved with either a uniform axial magnetic field or a periodic permanent magnet (PPM) focused field [11]. A solenoid electromagnet can generate strong (up to 2 T), spatially uniform, axial magnetic fields at the expense of relatively large system volumes and weights due to the mass of the solenoid and the requirement of an external power supply and cooling system. PPM stacks are considerably lower in mass and volume, requiring no external power supplies, but they produce lower fields with a spatially nonuniform
Brillouin field as a function of beam current and a variety of beam voltages and radii. The axially scalloped field may be unacceptable for applications that require tight dimensional control over the beam.

With the availability of rare-earth permanent magnet materials in a range of geometric shapes and properties, new mass- and volume-conserving magnetic structures are possible. The unprecedented coercivities of the samarium cobalt and Nd–Fe–B compounds, with their attendant resistances to demagnetization, make it possible to create exotic magnetic field configurations with rapid spatial variation and high intensity fields. These new geometric arrangements of permanent magnets are useful for both PPM and constant field focusing.

C. Rare-Earth Permanent Magnet Structures for Periodically Focused Fields

Fig. 19(a) is a longitudinal cross section of a conventional TWT PPM stack with indented iron pole pieces. In this design, the TWT vacuum jacket containing the RF circuit and electron beam is surrounded by a stack of alternating rings of permanent magnets and iron pole pieces. With their superior energy products and coercivities, samarium-cobalt rare-earth permanent magnets have replaced Alnico as the material of choice for PPM magnets, achieving substantial savings in mass and bulk. But the potential utility of the rare-earth materials goes far beyond mere substitution into conventional PPM designs. As described in [74] and [75], a hybrid iron-free structure composed of a stack of triangular cross section, rare-earth magnets with alternating axial and radial magnet orientations [Fig. 19(b)] can afford more than an order of magnitude savings in mass and bulk over a conventional PPM stack with iron pole pieces in the range of bore fluxes of 0.2 to 0.5 T. The hybrid triangular PPM stack creates a magnetic pole distribution that confines virtually all of the magnetic flux to the interior of the structure, which accounts for its high efficiency [76]. Comparative transverse cross sections of these two PPM geometries are shown in Fig. 19(d) and (e). Each structure was designed to produce an on-axis field of 0.45 T with a bore radius of 0.538 cm and a magnet period of 1 cm.

While the hybrid stack represents one of the most volumetrically efficient, high bore-field PPM designs that can achieved with rare-earth magnets, the design is hard to implement because of current difficulties in achieving radial magnetization in smooth-bore ring magnets with high coercivity. Also, there are fundamental limitations of the all-magnet geometry that make it difficult to insert shims to compensate for field irregularities incurred in the manufacture and assembly of the structure. A practical compromise design is the triangular iron-poled array [76], which introduces triangular cross-section iron pole-pieces between alternating axially oriented rare-earth magnets [Fig. 19(c)]. In this case, the iron-poled geometry can accommodate shims and the exclusive use of axially magnetized magnets simplifies fabrication. Although the triangular iron-poled array is not as volumetrically efficient as the hybrid stack, it still represents a factor of two savings in volume compared to the conventional PPM stack, as shown in Fig. 19(d) and (f).

D. Rare-Earth Permanent Magnet Structures for Constant Fields

Beam scalloping is an unavoidable consequence of PPM focusing and poses a potential problem for high power and millimeter-wave vacuum electronic amplifier applications because of the danger of beam interception on the walls of the RF circuit. To prevent or minimize beam interception, these devices require the finer beam control and confinement afforded by a uniform axial magnetic field. Traditionally, these fields are generated by electromagnets, which have the disadvantage of requiring external power supplies and either forced-air (for \( B_z < 0.5 \) T) or liquid cooling (for \( B_z > 0.5 \) T). With their high energy-products, rare-earth permanent magnet materials can supply uniform magnetic fields of practical magnitudes to cylindrical working volumes. The high coercivities and
Fig. 20. (a) Permanent magnet solenoid; (b) permanent magnet solenoid with the addition of a field-free, electron gun region. The broad white arrows indicate the direction of the magnetic field, the smaller black arrows indicate the direction of magnetization in the constituent permanent magnet pieces.

consequent magnetic rigidity of the materials allow the use of cladding to concentrate the fields in the working volume. Cladding has the advantage of both maximizing the field where it is needed most and minimizing the external stray fields that could potentially interfere with nearby electronic components and instruments.

References [77]–[79] describe the design of a permanent magnet solenoid that is capable of producing uniform axial magnetic flux densities of up to one-half the remanence of the supply magnet in a working volume that is long compared to its transverse dimension. Referring to Fig. 20(a), the flux is supplied to the working volume by an axially magnetized cylinder while the cladding is formed from a set of radially magnetized appliqués surrounding the supply magnet. By changing the shape and magnetization of the interior and exterior magnets, the field along the bore can be made uniform or caused to vary with axial position.

An experimental prototype of a permanent magnet solenoid was designed to provide a uniform axial guide field of 0.24 T over a 23-cm distance [80], [81]. The design featured a shielded, field-free region to house a thermionic electron gun together with penetrations in the magnet structure to simulate TWT access ports; the field-free region is illustrated in Fig. 20(b). The magnet structure was tested in conjunction with a 35-kW, 0.5-Perv electron beam (22 kV, 1.6 A) and achieved 98% beam transmission. The mass of the magnet structure was approximately 15 kg, which was an estimated one-third of the mass of an equivalent solenoid electromagnet (not including the power supply).

As a final example of rare-earth permanent magnet constant field structures, the magic sphere of Fig. 21 can produce multi-Tesla fields in an extremely compact volume [82]–[84]. As shown in Fig. 21(a), the magic sphere is con-
constructed from individually magnetized permanent magnet segments; to create an axially-directed field in the central cavity, the magnetization vectors of the segments vary twice as fast as the polar angle. The central cavity field is highly uniform, making it particularly suitable for mm-wave applications. The magnitude of the field, $B_{wr}$, in the cavity is given by

\[
B_{wr} = \frac{4}{3} B_0 \ln \left( \frac{r_o}{r_2} \right) \tag{20}
\]

where $B_0$ is the magnetic remanence, $r_o$ is the outer radius of the sphere, and $r_2$ is the radius of the central cavity. For example, with a desired central cavity diameter of 4 cm and using a magnet material with a remanence of 1.1 T, a 2 T cavity field can be achieved with a 15.6-cm diameter sphere massing approximately 16 kg. If the required working volume is smaller than the spherical central cavity, the unused portion of the cavity can be filled with a magnetic material with a magnetization counter to the field in the working volume, augmenting the working field [85]. The augmenting material can be oriented to form a thin, axial working space, as illustrated in Fig. 21(a), or to form an equatorial working space, as illustrated in Fig. 21(b). In the former case, the augmenting field may add as much as $B_0/3$ to the central field; in the latter case, the augmenting field may add as much as $2B_0/3$. If the desired working volume permits, the two augmenting methods may be combined to form a doubly augmented sphere.

VII. CONCLUSION

Unique materials will continue to play a significant role in advancing the capabilities of vacuum electronic devices. Thermal management issues and the onset of electromagnetic instabilities typically limit average power production at high frequencies. As the demand for additional power capability in the millimeter-wave bands continues to grow, thermal management technologies such as CVD diamond and porous metal cooling can be expected to play a critical role in future system designs. The clever application of lossy ceramic materials for the control of instabilities in overmoded structures represents another method of increasing the average power capabilities in devices such as gyro-amplifiers. The suppression of instabilities is also critical for obtaining higher bandwidth from gyrodevices and TWT’s. Additional goals for future vacuum electronic devices include obtaining higher overall system efficiencies and reducing the system physical size and weight. Technologies such as lightweight rare-earth permanent magnets and pyrolytic graphite are proving instrumental in meeting these demands.

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REFERENCES


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