Diamond Resistives – the ideal passive to reduce temperatures and keep low VSWR at high frequencies

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KEY WORDS: 5G wireless, resistors, power amplifiers, chemical vapor deposited diamond, voltage standing wave ratio, millimeter wave.

ABSTRACT

RF resistors able to operate above 8 GHz while handing >100 W are critical for successful operation of phased array radar and 5G wireless infrastructure. This requires a substrate material that maximizes heat removal whilst keeping parasitic reactance to a minimum. In this work it is demonstrated that this cannot be achieved with traditional substrates (AlN and BeO), but would be achievable by using CVD diamond. This will be illustrated primarily through the evaluation of resistor parameter "capacitance per watt."

INTRODUCTION

With the designation of the operating spectrum for 5G at above 6 GHz [1,2], and high-performance phased arrays radars operating in the X and Ku bands [3], there is significant drive for passive components able to handle high power density at higher frequencies.

To date beryllium oxide (BeO) and aluminium nitride (AlN) have been the preferred substrates for high power RF resistors. These ceramic materials have relatively high thermal conductivity and enable resistors to handle tens to hundreds of watts when operating at L and S bands (1-4 GHz). However, when operating from X band up to Ku band (8-30 GHz), the need to reduce resistor parasitic effects through a reduction in device surface area, leads to a diminished ability to dissipate only a few watts of power when using BeO or AlN substrates. This limitation will become a bottleneck against extending high power applications above S-band.

These trends mean that the frequency performance of even the simplest element, the resistor, becomes a key parameter to ensure a flawless behavior of the electronics. It should be noted that at high frequencies the impedance of a resistor cannot be defined as an ideal resistance, but its parasitic inductive and capacitive characteristics start dominating its behavior leading to signal distortion [4-6]. Additionally, there are many RF applications where resistors are used in termination and isolation requiring capability to dissipate large amounts of RF power.

Typically, RF resistors are made of a thin lossy strip of metal (TaN or NiCr) deposited on a dielectric substrate. For high power applications large amounts of heat must be handled and dissipated while ensuring operation temperatures below 125°C. The conflicting demands of minimizing the parasitic impedance of the resistors, through reducing resistor size and using low permittivity substrates [4], typically work against the requirement to maintain low operating temperatures with increasing power density.

In this work it will be shown that using CVD diamond substrates provides an optimum solution that enables RF resistors to operate above 8 GHz while handing over 100 W of power.

SUBSTRATES FOR GHz RESISTIVES

Table 1 summarizes the values of the key parameters affecting performance for the different high thermal conductivity substrates used in RF resistors. It is evident that AlN, with the highest permittivity and the lowest thermal conductivity will perform worse than BeO, with diamond excelling having the best combination of low permittivity and high thermal conductivity.

TABLE 1: Properties of typical materials used as dielectric substrates for RF resistives (@300k)

	ε_r	tan δ	κ (W/mK)	α (ppm/K)
AlN	8.8[8] (8.5GHz)	3.5×10^{-3} (8.5GHz)[8]	188[9]	3.55[12]
BeO	6.75[8] (8.65GHz)	4×10^{-4} (8.7GHz)[8]	260-300[10]	6.48[12]
Diamond	5.72[7]	5×10^{-5} (>1GHz)[7]	>2000[11]	1.79[12]

Diamond's permittivity is ~15-35% lower than those of BeO and AlN respectively and is stable to changes in frequency and temperature, varying by only 5% from low frequencies up to tens of GHz, and only shifting by 730 ppm/°C from room temperature up to few hundreds of °C (Figure 1-a) [7].

Stability of thermal conductivity as a function of temperature is also an important factor for successful operation of resistives at elevated frequencies. At 125°C the thermal conductivity for AlN and BeO are reduced by 30-40% from room temperature values (Figure 1-b). For the same span of temperature change the thermal conductivity of CVD diamond is changed by 10-15%.

Stability of RF and thermal properties enables a resistor made from purest single crystal diamond to potentially outperform AlN and BeO by factors of 10-15, as demonstrated through the ability of diamond to continue to dissipate higher level of the reflected power with increasing temperature.

Figure 1-b shows the thermal conductivity of two polycrystalline diamond grades [14] with bulk thermal conductivity of 1000 W/mK and 1800 W/mK, demonstrating significant improvement and stability over the thermal conductivities of AlN and BeO. In combination with its lower permittivity (Figure 1-a), CVD diamond resistives enable a 4-8x improvement in performance over that of resistives built on AlN and BeO substrates.

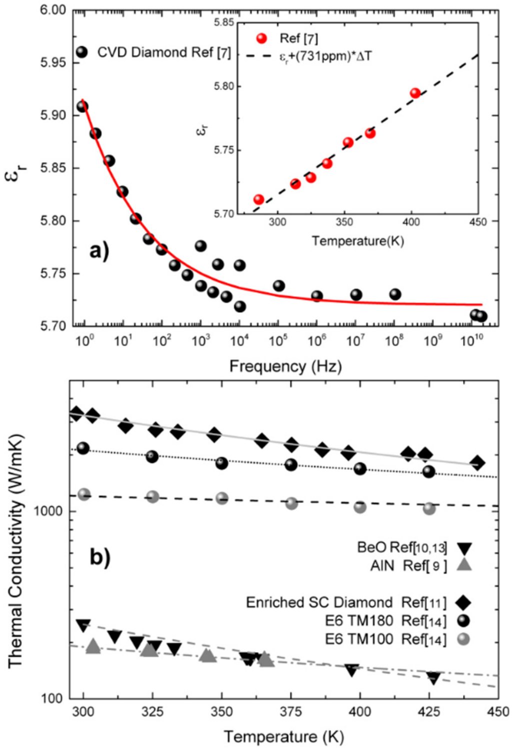

Figure 1: a) Real part of the diamond permittivity vs frequency [7]. Note that at high frequency (>10^8 Hz) it is almost independent of frequency. Inset, change of diamond permittivity vs temperature [7]. b) Thermal conductivity of the different materials used as a dielectric substrate in high power resistors [9-11,13,14].

FIGURE OF MERIT (CAPACITANCE/WATT)

To show the impact of the parasitic capacitance and inductance at GHz frequencies on the resistor's performance a standard lumped model of a thin resistor [4,6] is used (inset, Figure 2 a)). This includes the parasitic inductance of the resistor metallic film and contacts, and the parasitic capacitance of the structure. The series parasitic inductance arises from the metal thin film and contact pads, and varies with the mounting conditions of the resistor [4]. For single-sided mounted resistors exceeding 0.2 mm, the inductance approaches a constant value of 0.1 nH [5]. The parasitic capacitance arises from the self-capacitance of the resistor [15], and, to a greater extent, from the parallel capacitance between the resistor film and contacts to the ground plane [5]. Typically the deviation from an ideal resistor is given by the voltage standing wave ratio (VSWR) which for a resistor is calculated as:

$$\mathbf{VSWR=max\ (Z0,\ Z(v))\,/\,min(Z0,\ Z(v))}$$

with **Z0** the ideal resistance and **Z(v)** the impedance calculated from the resistor equivalent circuit.

The frequency at which the VSWR of the resistor reaches 1.25 (-19 dB), a common metric for the quality of a resistor, is shown in Figure 2-a), as a function of the parasitic capacitance. This figure clearly shows how the parasitic capacitance affects the behavior of the resistor. As an example, for a 50 Ω resistor operating at X-band, a parasitic capacity lower than 0.4 pF is needed to achieve a VSWR equal or lower than 1.25. If the frequency is increased to K-band, the capacitance needs to be half this value. As expected, increasing the resistance requires even lower capacitance values [4]. To calculate the capacitance of a single-sided mounted resistor in a given dielectric it was assumed that the thin film resistor is a very lossy transmission line [5]. For simplicity it is assumed that contacts and resistor area have similar width (W), and that contact length (Wc, see inset Figure 2-b) is fixed at 0.2 mm. The aspect ratio W/L of the resistor is also fixed to 0.5 for simplicity without loss of generality.

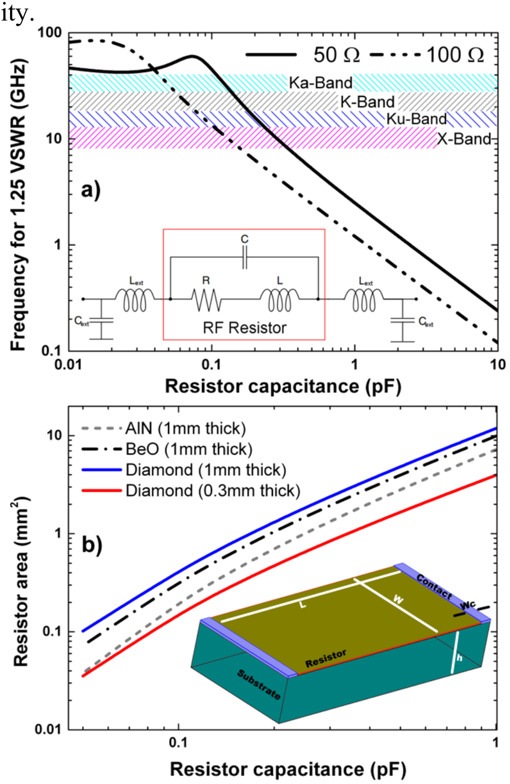

Figure 2: a). Frequency at which the VSWR of the resistor reaches 1.25 as a function of the parasitic capacitance for a 50 Ω and 100 Ω resistor and 0.1 nH. Inset: equivalent lumped circuit of a resistor. b) Calculated capacitances of a single-sided mounted resistor vs resistor area (0.5 aspect ratio) for different substrates. Inset: geometry of a resistor.

With these simplifications calculating the capacitance of the geometry is straightforward from the optimized design equations derived for calculating capacitances in micro-strips (described with more detail in ref. [16]). It should be noted that the impact of any top layer on the resistor are too small to be included in calculated results for the overall structure [16]. Finally, the total capacitances obtained for single-sided mounted resistors on different substrates as a function of resistor area, not counting the contacts in the area, but including its contribution to the total capacitance, are plotted in Figure 2-b. Trivially, the low permittivity of diamond yields the smaller capacitance per mm^2 when the thickness of the substrate is a constant for all the materials. This enables the use of thinner diamond substrates to maximize the cost/performance metric for the diamond solution. Following this, the capacitance of a resistor with a diamond substrate of 0.3 mm instead of 1 mm is also shown in Figure 2-b. Hence the capacitance per mm^2 shown in Figure 2-b, together with the curves shown in Figure 2-a, constitute a set of design rules providing the maximum area of a resistor ensuring operation at a given frequency keeping the VSWR below 1.25. On the other hand this capacitance per mm^2 determines the maximum power that can be dissipated in the resistor without exceeding a given temperature, typically 125°C.

In order to evaluate the maximum power that can be handled by each substrate a finite elements model was used for the single-sided mounted resistor and in accordance to the following design rules. It was assumed that the resistor was mounted in the center of a 50x20x3 mm^3 copper heatsink (400 W/mK) and attached by a standard 25 µm AuSn solder layer (57 W/mK). The dielectric substrate was set to 6x5x1 mm^3 for AlN and BeO with 3.5x3.5x0.3 mm^3 substrate size chosen for diamond, roughly an order of magnitude less material than that of BeO and AlN. The thermal conductivity of the different substrates was extracted from Figure 1-b. Finally, a 100 nm layer of TiN (7.6 W/mK) with a variable size (0.5 aspect ratio) option was added on top of the dielectric. It was assumed that the power density was uniformly dissipated in this layer. Natural convection (h=4.84 W/m^2) was set as a boundary condition for all the free boundaries but for the heatsink backplane which assumed to be at a fixed temperature (25°C). For simplicity and without loss of generality the size of the dielectric (which acts as a heat spreader) remained constant when reducing the size of the resistor (Figure 3, top sketch).

The results of this benchmark between substrates are summarized in Figure 3-a. In this figure the maximum power dissipated in the resistor per capacitance producing a differential temperature (ΔT) of 100°C is shown, depicting the power per capacitance of the different substrates. Note that to dissipate 100 W with a max ΔT of 100°C, the resistor on AlN needs to be much larger than the one using diamond, and thus according to Figure 2-b, its capacitance would also be larger, which ultimately, and from Figure 2-a, translate to a much operational lower frequency to maintain a <1.25 VSWR than an equivalent resistor on diamond (red dash line in Figure 3-a). These results are directly correlated with operational frequencies in Figure 3-b, from where it follows that for a 50 Ω resistor able to dissipate 100 W (100°C max ΔT) on AlN or BeO the frequency cut-off is limited to S-band (<5 GHz). In contrast, the use of diamond means that the operational frequency for a similar resistor exceeds 10 GHz for all the analyzed diamond grades with the theoretical limit reached at the K-band. It is worth noting that these theoretical results are in very good agreement with measurements on real resistors reported elsewhere [17].

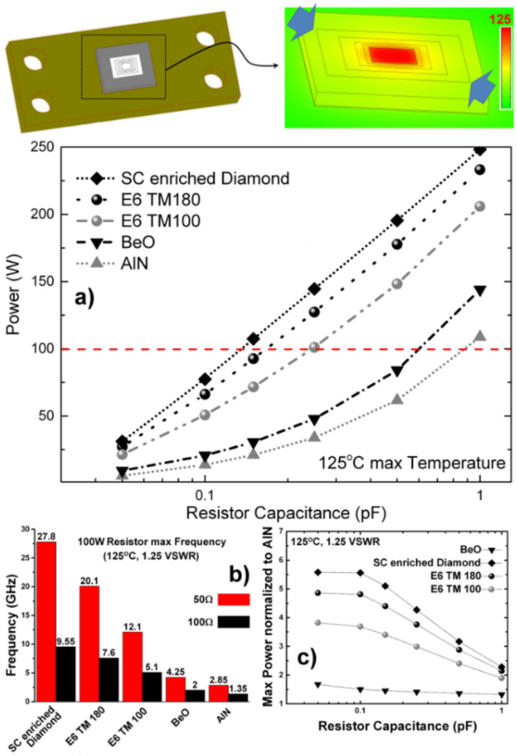

Figure 3: Top: sketch of the finite element simulation domain. a) Power per capacitance of the resistors with different substrates at a maximum peak temperature of 125°C. Note that diamond substrate is 0.3 mm (1 mm for AlN and BeO), the red dash line sets the 100 W limit. b) Maximum frequencies for a 50 Ω and 100 Ω resistor dissipating 100 W to operate below 1.25 VSWR. C), power per capacitance normalized to the resistor on AlN.

Finally, the power per capacitance normalized to the resistor on AlN is shown on figure Figure 3-c. For high frequency operation, in which small resistors are needed, CVD diamond offers up to ~4-5x more power dissipation than AlN and BeO due to its superb thermal conductivity. However, when the dimensions of the resistor are much bigger than the dielectric thickness, this advantage is reduced since the thermal management is dominated by the AuSn soldering layer and the copper heatsink.

Table 2 provides a comparison of the three resistive substrate options at 1 mm thickness for AlN and BeO and 0.38-mm for CVD diamond. CVD diamond with its lower permittivity and highest thermal conductivity yields the smallest capacitance per Watt value of the three substrates.

TABLE 2: Figure of merit. Lower capacitance per watt gives wider frequency response

	Substrate Thickness (mm)	Resistive Area (mm^2)	Capacitance/ Watt (pF/W)
AlN	1	18	0.012
BeO	1	18	0.007
Diamond	0.38	3.25	0.003

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k	thermal conductivity
ε_r	permittivity
$\tan\delta$	loss tangent
α	coefficient of linear expansion
Z_0	ideal resistance
$Z(v)$	impedance

CONCLUSIONS

It was demonstrated that by switching the substrate of high power RF resistors from AlN and BeO to CVD diamond it is possible to extend their operative frequency range well above X-band whilst handling powers above 100 W. This could offer a step change improvement towards minimizing distortion and complexity of high power electronics in 5G communications and military millimeter-wave devices operating in X-band and above.

References

[1] NGMN Alliance, 5G White Paper, https://www.ngmn.org/

[2] OFCOM, Spectrum above 6 GHz for future mobile communications, https://www.ofcom.org.uk.

[3] E. Brookner, Phased-Array and Radar Breakthroughs, 2007 IEEE Radar Conference, Boston, MA, 37-42, (2007)

[4] R.S. Johnson et al. Frequency response of thin film chip resistor, Proc. of the 25th CARTS USA 2005: 136-141. (2005)

[5] Z. Wang, J. Deen and A. Rahal, Accurate Modelling of Thin-Film Resistor up to 40 GHz, Solid-State Device Research Conference, 2002. Proceeding of the 32nd European, pp. 307-310, (2002).

[6] K. Steinberg et al, J.Appl.Phys. Microwave inductance of thin metal strips 108, 096102 (2010)

[7] A.Ibarra et al, Wide frequency dielectric properties of CVD diamond, Diamond and Related Materials, 6, 856-859 (1997).

[8] W.B. Westphal and A. Sils. Dielectric constant and loss data. Vol. 72. No. 39. Air Force Materials Laboratory, Air Force Systems Command, (1972).

[9] J. E. Graebner et al. Report on a second round robin measurement of the thermal conductivity of CVD diamond. Diamond and Related materials 7.11 1589-1604, (1998).

[10] G.P. Akishin et al. Thermal conductivity of berylli16um oxide ceramic. Refractories and Industrial Ceramics 50.6 465-468, (2009).

[11] L. Wei et al. Thermal conductivity of isotopically modified single crystal diamond. Physical Review Letters 70.24 3764. (1993).

[12] G.A Slack & F. Bartram. Thermal expansion of some diamondlike crystals, Journal of Applied Physics 46.1 89-98. (1975).

[13] D.A. Ditmars and D. C. Ginnings, Thermal Conductivity of Beryllium Oxide From 40° to 750° C , Journal of Research of the National Bureau of Standards 59, 2775, (1957).

[14] S.E. Coe and R. S. Sussmann. Optical, thermal and mechanical properties of CVD diamond. Diamond and Related Materials 9.9, 1726-1729, (2000).

[15] S. Demurie and G.t De Mey. Parasitic capacitance effects of planar resistors. IEEE Transactions on Components, Hybrids, and Manufacturing Technology 12.3 348-351. (1989).

[16] E. Bogatin, Design rules for microstrip capacitance, IEEE Transactions on components, hybrids, and manufacturing technology 11.3, 253-259, (1988).

[17] M. Bailly Diamond Rf ™ Resistive the answer to high power and low capacity, Microwave Journal 53.11 94-100, (2010).