Overcoming High Power Limitation of Thin Film Resistors at GHz Frequencies Using CVD Diamond Substrates

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Abstract

We show RF resistors able to operate above 8 GHz while handing >100 W can be obtained by switching the resistor substrate to CVD diamond. Obtaining high power resistors able to operate above S-Band requires reducing its parasitic electrical characteristics to a minimum. In this work we demonstrate that this cannot be achieved with traditional substrates (AlN and BeO), but it is straightforward when using CVD diamond. This is clearly illustrated through the resistor's parameter 'capacitance per watt'. We also compare the performance of the different substrates for high power resistors using a model of a 75 W Wilkinson divider operating at 10 GHz.

INTRODUCTION

Increasingly the millimeter-wave market demands solutions that simultaneously offer GHz performance at high power levels. With proposals for 5G operating 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 densities at higher frequencies. 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 these 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]. In addition there are many applications in RF design where resistors are used in termination and isolation requiring capability to dissipate large amounts of RF power, requiring excellent thermal management.

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 by to ensure operation temperatures below 125°C. The conflicting demands of minimizing the parasitic impedance of the resistors, reducing resistor size and use of low permittivity substrates [4], typically work against the challenge to keep low operating temperatures with increasing power density. To date beryllium oxide (BeO) and aluminum 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/hundreds of watts when operating at L and S bands (1-4 GHz). However the trade-off between maximizing the dissipated power and reducing resistor parasitic effects leads to a maximum dissipation of few watts when operating from X-band up to Ku-band (8-30 GHz) when using BeO or AlN substrates. This limitation in power is increasingly a bottleneck for extending high power applications above S-band. However, we present here a solution enabling RF resistors able to operate above 8 GHz while handing over 100 W by using CVD diamond as the resistor substrate.

MATERIALS PROPERTIES

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. 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 (see Fig. 1-a) [7]. Temperature is also important when considering the thermal conductivity, since at

TABLE I
SOME PROPERTIES OF THE MATERIALS USED AS DIELECTRIC SUBSTRATES IN HIGH POWER RESISTORS (300 K). (PERMITTIVITY, LOSS TANGENT, THERMAL CONDUCTIVITY AND THERMAL EXPANSION)

	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]

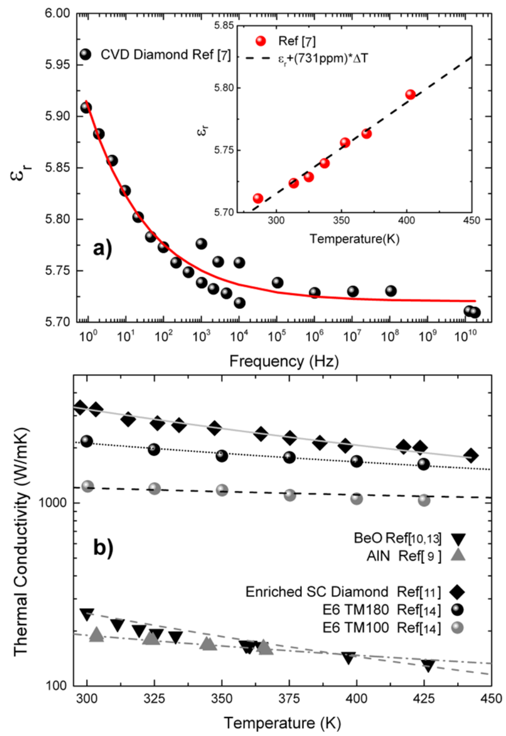

Fig. 1. a) Real part of the diamond permittivity vs frequency [7]. Note that at high frequency (>10^8 Hz) it is almost independent of frequency. Inset, change of diamond permittivity vs temperature [7]; b) Thermal conductivity of the different materials used as dielectric substrate in high power resistor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

125°C its value is reduced by 30-40% from room temperature values (see Fig. 1-b). Thermal conductivity of the purest single crystal diamond may exceed AlN and BeO by a factor of ~10-15, which as a rough approach means that a resistor using this substrate may be able to handle 10-15 times more power. In Fig. 1-b we also show the thermal conductivity of two polycrystalline diamond grades [14], one with bulk thermal conductivity of 1000 W/mK (TM100) and one with thermal conductivity of 1800 W/mK, representing a 4-8x improvement over the thermal conductivities of AlN and BeO, while simultaneously having a low permittivity (Fig. 1-a).

CAPACITANCE PER WATT:

To show the impact of the parasitic capacitance and inductance at GHz frequencies on the resistor's performance we used a standard lumped model of a thin resistor [4, 6]. 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 $\mathbf{VSWR} = \mathbf{max}(\boldsymbol{Z_0}, \boldsymbol{Z}(\boldsymbol{v}))/\mathbf{min}\left(\boldsymbol{Z_0}, \boldsymbol{Z}(\boldsymbol{v})\right)$, with Z_0 the ideal resistance and $\boldsymbol{Z}(\boldsymbol{v})$ 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 Fig. 2-a as a function of the parasitic capacitance. This figure clearly shows how the parasitic capacitance affects the behavior of the resistor, for example 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 we considered the thin

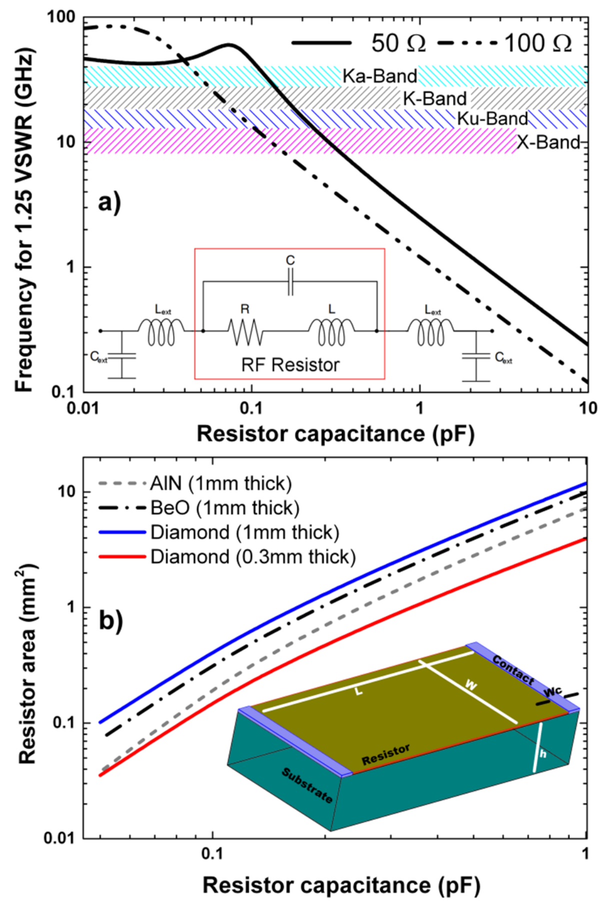

Fig. 2. a) Frequency at which the VSWR of the resistor reaches 1.25 as a function of the parasitic capacitance for a 50 Ω and 100 Ω resistor and 0.1 nH. Inset: equivalent lumped circuit of a resistor; b) Calculated capacitances of a single-sided mounted resistor vs resistor area (0.5 aspect ratio) for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

film resistor is considered as 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 Fig. 2-b) is fixed to 0.2 mm. The aspect ratio W/L of the resistor is also fixed to 0.5 for simplicity without loss of generality. With these simplifications calculating the capacitance of the geometry is straightforward from the optimized design equations derived for calculating capacitances in microstrips (described with more detail in ref. [16]). We note that we did not included in the calculations any layer on top of the resistor (which are the same with independence of the substrate) since their overall effect is small for this 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 Fig. 2-b. Trivially, the low permittivity of diamond yields the smaller capacitance per mm^2 when 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 Fig. 2-b. Hence the capacitance per mm^2 shown in Fig. 2-b, together with the curves shown in Fig. 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 we modeled by finite elements the single-sided mounted resistor according to these design rules. For this, we assumed 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 while for diamond a smaller size was chosen, 3.5x3.5x0.3 mm^3, i.e. one order of magnitude less material than for BeO and AlN. The thermal conductivity of the different substrates was taken from Fig. 1-b. Finally, a 100 nm layer of TiN (7.6 W/mK) with a variable size (0.5 aspect ratio) was added on top of the dielectric and a homogeneous power density was dissipated in this layer. Also natural convection (h=4.84 W/m^2) was set as a boundary condition for all the free boundaries but the heatsink backplane which is kept 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 (See Fig. 3, top sketch).

The results of this benchmark between substrates are summarized in Fig. 3-a. In this figure the maximum power dissipated in the resistor per capacitance producing a ΔT=100°C is shown, i.e. it clearly shows the power per capacitance of the different substrates. Note that to dissipate

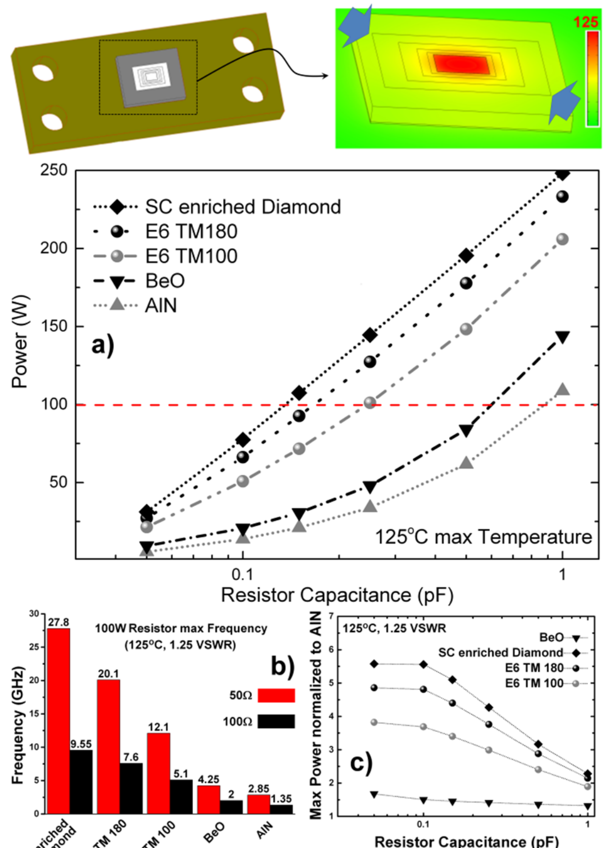

Fig. 3. Top: sketch of the finite element simulation domain. a) Power per capacitance of the resistors with different substrates at a maximum peak temperature of 125°C. Note that diamond substrate is 0.3 mm (1 mm for AlN and BeO), the red dash line sets the 100 W limit; b) Maximum frequencies for a 50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

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 Fig. 2-b, its capacitance is also bigger, which ultimately, and from Fig. 2-a, yields a much lower frequency to operate below 1.25 VSWR than an equivalent resistor on diamond (see red dash line in Fig. 3-a). These results are directly correlated with operational frequencies in Fig. 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, being the theoretical limit in the K-band. It is worth nothing that these theoretical results are in very good agreement with measurements on real resistors reported elsewhere [17].

Finally, the power per capacitance normalized to the resistor on AlN is shown on figure Fig. 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 thanks 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.

Wilkinson Divider/Combiner

The performance of a single stage Wilkinson divider has been chosen to illustrate the impact of the high frequency behavior of the resistors with different substrates (see Fig. 4, sketch). A Wilkinson divider/combiner is a well-known and omnipresent circuit able to provide isolation between the output ports while maintaining a matched condition for all the ports [18]. However keeping this ideal behavior relies on the isolation resistor, which should satisfy the relation $= 2Z_0$, with Z_0 the impedance of the line (fixed at R=50 Ω). Hence any deviation of the resistor impedance (ideally 100 Ω) will result in a deviation from the ideal characteristics of the divider. The performance of the divider is typically given thorough the S_{11} and S_{21} parameters of its scattering matrix, which give information about the reflection coefficient in port 1 and the transmission coefficient between ports 1 and 2 [19]. For an ideal device at the design frequency $|S_{11}|$ is 0 and $|S_{21}|=|S_{31}|=0.5$ (-3 dB) [19]. These ideal characteristics have been calculated for a 10 GHz (X-band) device following the derivation made by Cohen in [20] and the results are shown in Fig. 4. Since the isolation resistor can absorb a large amount of power when signals on ports 1 and 2 differ either in phase or amplitude, we set a maximum operational power of 75 W (max ΔT=100°C). Hence this power limit sets the parasitic capacitance for the different substrates (from Fig. 3-a), and thus determines the impedance of the resistor at any frequency (calculated from the equivalent circuit show in Fig 1-a, inset). When the deviation from the ideal impedance is included in the isolation resistance of the Wilkinson divider model [20], the $|S_{11}|$ and $|S_{21}|$ characteristics shown in Fig. 4-a and Fig. 4-b are obtained for each substrate. From these results it follows that resistors using good quality diamond are able to offer excellent performance at 10 GHz; $|S_{11}|$ is at least -20 dB at the frequency design showing a bandwidth of 9 GHz ($|S_{11}|$<-15 dB, black dotted line in Fig. 4-a). On the other hand, for these particular frequency and power conditions the use of low grade diamond as a resistor substrate represents the lower limit to ensure a good performance for the chosen Wilkinson divider ($|S_{11}|$≈-15 dB). In comparison Wilkinson dividers making use of resistors on AlN and BeO substrates show very poor characteristics around the design frequency with $|S_{11}|$ well above -10 dB and $|S_{21}|$ widely deviating from the optimal -3 dB (see Fig. 4-b).

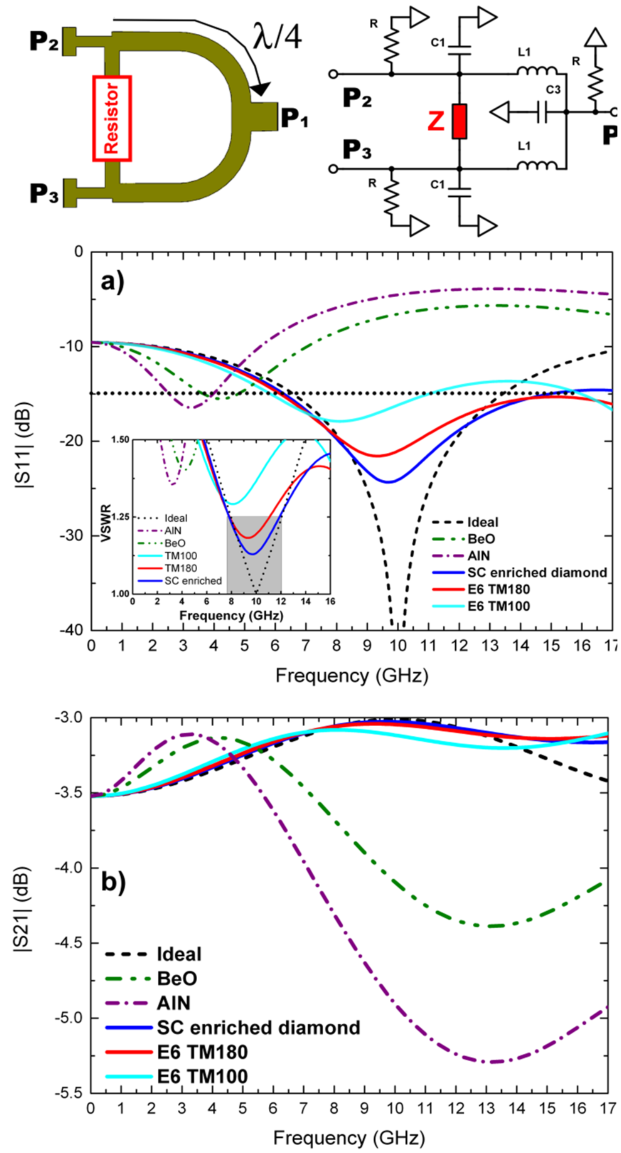

Fig. 4. Top: Typical representation of an RF Wilkinson divider and its equivalent representation using lumped ideal elements. For 10 GHz central frequency R=50 Ω, L1=1.125 nH, C1=0.225 pF and C3=2C1. a) $|S_{11}|$ vs frequency of the Wilkinson divider using 100 Ω resistors on different substrates. Inset VSWR of the Wilkinson dividers in which the 1.25 VSWR region has been highlighted; b) $|S_{21}|$ vs frequency of the Wilkinson divider using 100 Ω resistors on different substrates

Conclusions

We have 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.

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Acronyms

CVD: Chemical Vapor Deposited
VSWR: Voltage Standing Wave Ratio
BeO: Beryllium Oxide
AIN: aluminum nitride