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► **To cite this version:**

Bruno Allard, Cyril Buttay, Christian Martin, Hervé Morel. Considerations for High Temperature Power Electronics. 18th International Symposium on Power Electronics Ee2015, Oct 2015, Novi Sad, Serbia. hal-01372146

HAL Id: hal-01372146

<https://hal.science/hal-01372146v1>

Submitted on 26 Sep 2016

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Considerations for High Temperature Power Electronics

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Abstract: High-temperature electronics is driving large development efforts regarding many issues among which the objective of integration. The main objectives for a higher level of integration come with the constraint of increased reliability. At converter level, these objectives face many challenges and 3 of them are discussed here with indication of results contributed by Ampere-lab.

Keywords: High temperature, power electronics, passive devices, wide band-gap devices, packaging

1. Introduction

“High temperature” means different things to different applications. In high voltage systems (such as power distribution), where silicon-based diodes or thyristors are limited to 125°C maximum junction temperature, an ambient of 100°C would be considered insanely high, whereas running in an environment as high as 150°C is already pretty common for some automotive systems.

Even when considering “classical” vehicles (as opposed to hybrid or full electric cars), the cost of the electrical system is more than that of the internal combustion engine (ICE) and its associated transmission [1]. Under the hood, temperatures can reach or exceed 140°C (for example, the rectifier diodes at the back of the alternator can operate above 160°C junction temperature [2]). At the opposite, temperatures can drop to -40°C in some places of the car.

In hybrid vehicles, it is possible to take advantage of the ICE cooling loop to extract heat from the power electronic systems, but the water can reach up to 120°C [1], so there is little headroom when working with 150°C or 175°C-limited silicon devices. New wide band gap materials such as Carbide Silicon or Gallium Nitride promise better performance with higher operating temperature and breakdown voltage [3].

In aircraft application, converters should be placed as close as possible to the actuator they control. This implies that some converters will be subject to harsh environment. For example, some of them will have to operate near the jet engine, with ambient temperature ranging from -55°C to 225°C [4].

Obviously very high reliability is expected from these systems, despite long operating life (10 - 30 years) plus frequent deep thermal cycling (several takeoff-landing per day). Targeted voltage in aircraft and automotive applications converge to 600V for power devices and 5V-to-30V for low-voltage circuits (drivers, sensors...).

Passives are still necessary for “high temperature” power electronics and some technologies are presented in this paper to meet these requirements. Typical requirements for passives components in motor drive systems are EMI input and output filters, DC-link capacitors, decoupling capacitors for low-level electronics as well as magnetic cores for isolated power supplies and chokes.

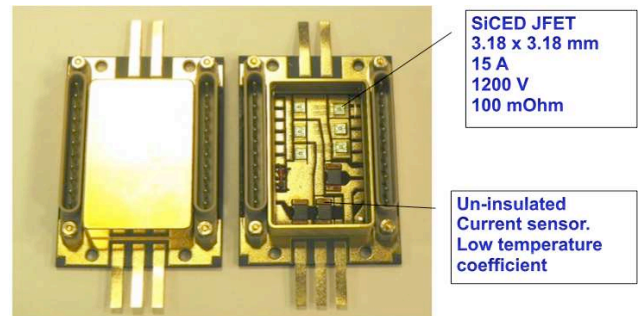


Figure 1: Demonstration of the benefits of WBG power devices wrt power density [5]

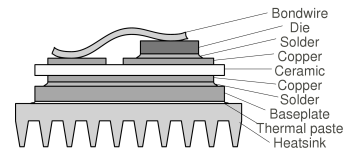


Figure 2: Schematic of a power module and related issues

Fig.1 [5] pictures the possible integration offered by wide band-gap (WBG) devices: the power density is increased 10 times at least. However limitations still preclude high-temperature operation. A compact module has been demonstrated in [6] that illustrates the main challenges to solve: passive devices, wide band-gap devices and packaging and interconnections (fig. 2). These issues are discussed from a state of the art point of view and the

perspectives of the contributions developed at Ampere-lab.

2. Packaging and Interconnection

Most packaging solutions have been developed for mild ambient [7], and require a complete redesign to cope with high temperature environments. Elements such as the die-attach, the silicone gels, or the plastic housing can only sustain a limited temperature.

Furthermore, most “high temperature” applications have to endure deep thermal cycling; the temperature of their environment can change dramatically. For example, systems designed to be located near the jet engine of an aircraft are submitted to an ambient temperature that ranges from -55 to 225°C [4]. As we can see in Figure 2, a power module is a stack of many materials, creating many interfaces. When such stack is submitted to thermal cycling, all parts tends to expand differently (as they all have different coefficients of thermal expansion), creating stresses at the interfaces. During the life of the power module, part of these stresses accumulates, creating fatigue and eventually failure.

This phenomenon is already present with standard, silicon-based components, but becomes even more critical with high-temperature applications because of their increased operating temperature range.

2.1 Focus on the die-attach

An example of packaging element that must be re-designed when increasing the temperature range is the die-attach. In Power electronics, dies are bonded to their substrate using solder (Figure 1). This solder must remain solid over the whole operating range of the power module, and yet the melting point of the solder must be low enough so that nothing is damaged during the assembly process.

In classical power modules, die-attach is made using “high temperature” lead-rich solder alloy [7], which melts at 312°C, or with other alloys which have an even lower melting point [8]. Although this melting point is higher than the maximum targeted operating temperature, a wide safety margin must be ensured between the maximum operating temperature and the melting point: the closer you are to the melting point, the worse the mechanical properties of the solder alloy. This is defined by a ratio, called the homologous temperature, defined as T_0/T_M

where T_0 and T_M are the maximum operating and melting temperatures respectively. It is considered that the mechanical properties of a material degrade above $T_h=0.5$ [10], although values as high as 0.85 are not uncommon in electronics.

For High Temperature applications, T_0 is high (above 200°C), resulting in the need for very high T_M solder alloys. This high temperature soldering process in

turn creates residual stresses in the assembly. Increasing T_0 further, the soldering alloy has to be replaced by a new composition. To avoid the race between T_0 and T_M , alternatives solutions are being evaluated.

2.2 Alternative interconnexion options

Semikron has developed sintering of micrometer-sized silver powder [10]. With this technique, a joint is obtained by applying pressure (40MPa) and temperature (about 250°C). As the die-attach material is pure silver, its melting point is expected to be 961°C, and therefore will operate at very low homologous temperature. To avoid the use of pressure (which requires dedicated tooling), researchers at the Virginia Tech. have presented a silver sintering solution using nanometre-sized powder [11, 12]. Experiments performed at Ampere-lab show that the addition of a light pressure (in the order of a few MPa, fig. 3) is still helpful with this nano-Ag paste to get a good bond. Silver sintering gives good results compared to Epoxy-based die attach or Au-Ge solders [13].

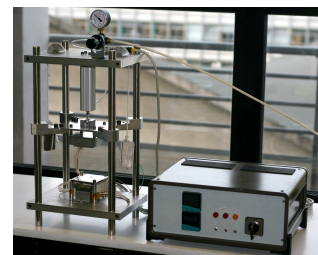


Figure 3: Heating press developed at Ampere-lab for the die attach operation

Another approach is the Transient Liquid Phase Bonding (TLP) [14]. With this technique, a low-melting point metal (or alloy) will diffuse into a solid phase. Once it is completely diluted into the solid phase, the melting point of the newly formed alloy will be much higher than the process temperature. Such techniques have been applied to Au/Sn alloys [15] and In/Ag [16], among others. Tests at Ampere-lab show that Au/Sn TLPB die-attaches require a thick layer of gold (10µm) to be deposited to the parts to bond (including the die), what makes this solution difficult to implement. Advantages of this solution are that a good bonding can be achieved in air and that it is a “clean process”, with no organic materials involved (if pre-forms are used).

3. Passive devices

3.1 Capacitors

High temperature capacitor technologies are based on the different dielectrics listed in the Table 1 and fig. 4. Most experimental results are obtained from the test setup in fig. 5. Tantalum-based capacitors

are dedicated to low-voltage applications, less than 50 V [17,18]. Metalized films like the Mica are mainly used for high-voltage applications. The minimum dielectric thickness available in industrial processes is too large to reach high energy density at low and medium voltage range. For mid-voltage range, as DC-link capacitors (1kV-5 μ F), performances of dielectric films (PPS-based) and High-K ceramics are quite similar until 150°C/175°C.

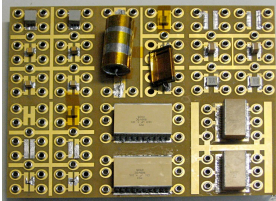


Figure 4: Test board for high-temp characterization of passive devices

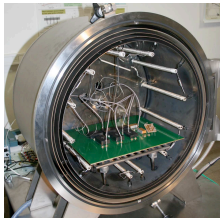


Figure 5: Experimental setup for high-temp characterization

Films are lighter but more bulky. Films will be preferred regarding the cost and the failure mode, which is most of the time an open circuit. However, at higher temperatures, over 200°C, available film capacitors (Mica, PTFE) demonstrate a much lower energy density than ceramics. The PPS film presents an excellent stability of the critical parameters (dielectric constant, dissipation factor, insulation resistance) with temperature but it is able to withstand high temperature, nearly 200°C, only during a short transient. For continuous operation at 200°C, Low-K ceramics are extremely stable and industrially ready [19]. They can be used as Common Mode (CM) capacitors or low-voltage decoupling capacitors. High-K ceramics present a strong non-linear behavior with the temperature and the polarization [20, 21, 22]. For instance, X7R's capacitance decreases up to 60% at high DC-bias voltage and 200°C. Nevertheless, today, this High-K ceramics ensure the best performances at high temperature. Ceramic dielectric is not affected itself by high temperatures due to high firing temperatures, but electrodes and terminations are sensitive to thermal and mechanical stress [23]. Space, oil drilling and military industries mainly use these high-temperature capacitors. Long-term and reliability data are relatively rare and need to be investigated for aircraft or automotive applications.

3.2 Magnetics

Several magnetic materials listed in Table 2 are potentially interesting to be used at high temperature. Some Fe-Co or Fe-Si alloys show good high temperature characteristics [24]. However, they are not well adapted to power electronics because they are mostly dedicated to low frequency applications, below 10 kHz. Powder cores, which are distributed air-gap, are naturally able to work until the iron Curie temperature but the polymer binder limits the core lifetime to some hundreds of hours at 200°C [23].

Some ferrites could meet the high temperature requirements, but with a very low saturation flux density and an increase of losses with the temperature. It reduces the use of ferrites to low power converters like isolated driver supplies as CM choke or transformer. Amorphous or nano-crystalline ribbons are today the better magnetic material for power converters and they have also a good behavior at 200°C. Losses are not affected by the temperature but the permeability decreases.

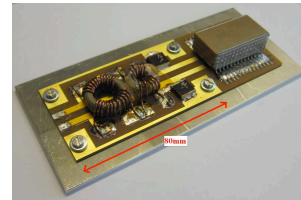


Figure 6: Discrete filter module for high-temp operation

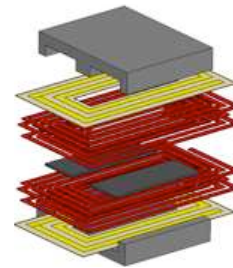


Figure 7: Schematic of integrated planar filter

Few years ago, the permeability range was extended to low permeability, about 200, and these materials are becoming industrialized [25]. Then, they cover all power electronics needs, like: boost inductor, line inductor, CM choke [26] or Flyback transformer. Core geometries are limited to a tore, C or U cores and cores smaller than a centimeter are not available. Nano-crystalline ribbons are very brittle but no coating is available at 200°C and some nano-crystalline materials are sensitive to ageing [23].

3.3 More integration

Towards the IPEM concept (Integrated Power Electronics Module) at higher temperatures, some solutions could be considered. Fig. 6 presents a discrete filter while fig. 7 gives an overview of an

integrated planar filter. For capacitors, Multilayer Ceramic Capacitors (MLCC) geometries are very flexible (with holes, angles, disk) but the stacked structure has to be kept. Films are compatible with a PCB integration but capacitance values will be low. For magnetic devices, limitations are mainly packaging, especially for powder cores and nano-crystalline ribbons but powder cores and ferrites could be molded with 3D geometries. Fe-Amorphous ribbons are much less brittle than nano-crystalline ribbons with lower performances. However, they are better than ferrites and planar core structure could be considered for power inductor or transformer for mid-power range (1-10kW).

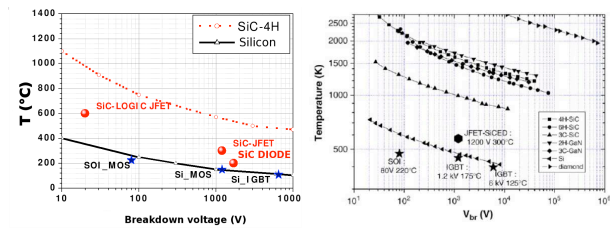


Figure 8: Theoretical temperature limit for operation of various devices

4. Wide band-gap devices and modules

Wide band gap semiconductor materials have superior electrical characteristics compared with Si. Various factors of merit have been defined to point out the benefits of some of them over the others. Among all these semiconductors, diamond has the widest bandgap; consequently it also has the highest electric breakdown field. SiC and GaN have similar bandgap and electric field values, 10 times higher than Si and GaAs. Therefore they are able to operate at higher temperatures.

Figure 8 shows the theoretical operating temperature limits of commercials or lab-demonstrators as measured at Ampere-lab. It clearly appears that Si (or SOI) is closed to its theoretical limits. Besides, apart from packaging considerations, SiC, GaN and C offer a great margin. In addition, among the various physical parameters, the drift saturation velocity value makes SiC and GaN more interesting at high switching frequency than Si or SOI, with lower switching losses' values. GaN and SiC in terms of "pure performances" are almost equivalent.

SiC technology is the most mature one among the other wide band gap semiconductors concerning high temperature electronics (Table 3). It is significantly mature since the 80's. Material processing problems have been mostly solved and

100mm wafer are now available. Various high-power switches operating at high-temperature have been demonstrated. Among them diodes and JFETs are on to be commercialized and high temperature operations has been demonstrated. Considering power-conversion chain, if power-switches are available, high temperature control circuits are still missing.

High-temp. electronic applications	Peak Ambient	Chip Power	Current Technology	Future Technology
Automotive Engine control Electronics On-cylinder & Exhaust Pipe Electric Suspension & Brakes Electric/Hybrid Vehicle	150°C 600°C 250°C 150°C	<1kW <1kW >10kW >10kW	BS & SOI NA BS BS	BS & SOI WBG WBG WBG
Turbine Engine Sensors, Telemetry, Control Electric Actuation	300°C 600°C 150°C 600°C	<1kW <1kW >10kW >10kW	BS & SOI NA BS & SOI NA	BS & SOI WBG WBG WBG
Spacecraft Power Management Venus & Mercury Exploration	150°C 300°C 550°C	> 1kW > 10kW ~ 1kW	BS & SOI NA NA	WBG WBG WBG
Industrial High Temperature Processing	300°C 600°C	< 1kW < 1kW	SOI NA	SOI WBG
Deep-Well Drilling Oil and Gas Geothermal	300°C 600°C	< 1kW < 1kW	SOI NA	SOI & WBG WBG

BS = bulk silicon, SOI = SOI, NA = not presently available, WBG = wide bandgap (SiC, GaN, C)

Table 3. Future of power electronic applications in H-T° environment

4.1 Gallium Nitride material and devices

The properties of GaN have been used for the last decade essentially to make blue led for optical drive or lighting. If developments mainly focused on optoelectronics and radio frequency, their properties were explored recently to create devices for high power and high efficiency applications.

GaN is III-V semiconductor with wide direct band gap, very low concentration of minority carriers, good thermal conductivity and high breakdown voltage [27]. The main limitation of the development of GaN is to obtain good quality substrates, thick enough to hold high electric fields. Gallium is a rare material so it is difficult to envision obtaining bulk substrate in gallium nitride. The main solution is to grow GaN on other substrates such as silicon, carbide silicon or Sapphire [28]. The main limitations for sapphire are mismatches of lattice structures that induce a lot of crystal defects in GaN and the lower thermal conductivity [29]. Carbide Silicon is a good candidate because their properties are close to GaN but SiC is 100 times more expensive than silicon so it isn't economically viable [30]. The third candidate is the silicon: the main advantages are the maturity of the process and the available infrastructure. As a consequence, GaN wafers are still more expensive than SiC wafers, especially for thick GaN epilayer useful for high-voltage devices. Researchers work to develop a process compatible to run on a standard CMOS line [31]. However, GaN does not have a

native oxide unlike Si nor SiC. More studies are underway to find a suitable a reliable oxide making GaN-MOSFET realistic [32].

4.2 GaN devices

The properties of GaN permit to power devices to work in high temperature or corrosive environment. The new devices offer high voltage and low on-resistance that enable important reduction in energy consumption in end-applications. Figures of merit for GaN devices have one or two order of magnitude better than Si device. The GaN RF devices are commonly used for high frequency application up to hundreds of GHz [33] such as telecommunication.

Different structures have been explored for (vertical) power device. Toyota explores vertical structures such as AlGaN/GaN HFET or UMISFET but these structures have low breakdown voltage, receptively 50V and 180V [34]. Vertical structures seem to have generally low breakdown voltage [35].

The preferable structures are actually lateral MOSFETs or HFETs. These devices use the properties of hetero-structure at the interface of AlGaN and GaN materials. A 2D gas of electrons enables to obtain very high mobility in the device and the quasi-absence of holes in GaN HFET structure thus eliminating the minority carrier effect in reverse recovery charge and then reducing the recovery time [36, 37]. The HFET structure on Si-substrate allows a good trade-off between performances with a high electric field around 1.0MV/cm and cost when using a 4in Si-wafer with AlGaN epitaxial layer [38]. The GaN-based LED market demands will probably lead to a significant cost reduction in 4in GaN epi-wafer. The comparison of GaN and SiC devices should now take this point into consideration.

4.3 GaN integrated circuits

As for SiC the main constrains to design GaN-ICs is that P-type transistors are not available nor reliable MOSFETs. Digital and analogue functions have been developed specially for RF applications [39]. They are based on the Direct-Coupled FET Logic (DCFL) (as well as for SiC). GaN technology is more sensible to temperature than SiC one. The most advanced GaN-IC is a 3-stage amplifier presenting a 22dB gain at 26GHz [40].

4.4 Silicon-Carbide devices

SiC power devices have been demonstrated and probably the SiC-MOSFETs and SiC-IGBTs are the awaited candidates. The SiC-JFET is commercially available and practical applications have been developed.

Recently, the first SiC-based integrated circuit has been announced [41]. It should eventually allow very

high temperature drivers or monolithic integration of drivers and power devices. However a lot of work is still needed to produce an embedded power supply. First SiC-IC demonstrations have been presented in the mid-90s. Thanks to the increase in market demands in various fields (Table 3), new investigations have been motivated.

Most of the basic functions of electronics have been demonstrated using SiC (more marginally in GaN). After reliable high power switches, several teams are now focusing on the achievement of reliable and efficient compact integrated systems, composed of both power and control parts. Concerning the control side, analogue functions (amplifiers, comparators, clock) able to operate for more than 6000 hrs at 500°C without significant degradations have been demonstrated [42]. Gate drivers [43, 44] and control circuit [45] have been successfully tested at 300°C. More recently, smart-power application benefits have been illustrated [46, 47] and a fully integrated boost converter has been fabricated [48].

Both NMOS, CMOS and JFET/MESFETs based-logic have been implemented and their high-temperature operation capabilities have been investigated. Despite its normally-on related issues, the JFET/MESFET technology is the most stable one for high temperature as SiC-MOSFET are suffering from their poor oxide reliability at very high temperature. A bipolar-based logic has also been investigated [49]. Non-volatile memories have also been fabricated and successfully tested at 200°C [50] but subject to the relaxation phenomenon (loss of data in 11 days at 300°C).

In most of the high temperature studies, circuit degradations are mainly related to non-semiconductor alterations: interfaces and metallic interconnections. Packaging is then the priority issue in order to guaranty a long-term reliability.

4.5 CMOS SOI Drivers

Most high temperature converter use control circuits made with Silicon-On-Insulator (SOI) substrate. Honeywell has developed many circuits for oil well applications, able to operate in the range of -55 to +225°C for more than 5 years (50000 hours @ 225°C) [51]. One year at 300°C has also been reported using a technology as old as 1998 [52]. More recently, a numeric platform operating at 250°C has been presented. This platform (reconfigurable processor for data acquisition) is composed of FPGA-EEPROM-SRAM [53]. In Europe, the companies Easii-XREL or Cissoid also design SOI circuits for high temperature, including MOSFET drivers [54].

Thanks to SOI maturity, high temperature hybrid system integration has been demonstrated (Univ. Arkansas). However the demonstrated drivers still

suffer the lack of strong isolation functions (control signal and energy) and protection functions (auto-protection, saturation protection) with a satisfying trade-off against EMI. Analog Device commercialized an isolated amplifier but EMI level is high and power consumption not acceptable [1]. A similar coreless isolation option is experimented by ROHMS and an impressive isolation level (2500V, 75kV/ μ s) is obtained at the penalty of an increased EMI source [2]. Ampere-lab is participating to many projects (SEFORA, COTECH, THOR) devoted to SOI-driver development (240°C, Fig. 9). The isolation functions are studied using discrete nano-crystalline transformers. The diameter of 1cm is acceptable in case of multiple supply outputs on secondary. It is the easiest solution to succeed 1kV isolation and low leakage because of a high permeability (100000 at ambient T° but loss of 50% à 220°C). Common-mode capacitors are the limiting factor (immunity to dV/dt). Low-permeability nano-crystalline is considered for a fly-back configuration. Integration is addressed with coupled inductances shielded with high Curie-point ferrites (yttrium indium garnet). The capacitive coupling has been experimented but is only suitable for signal isolation if limited dV/dt immunity is tolerated. Finally piezoelectric transformers are considered if high Curie-point ceramics can be manufactured and providing a tolerable mechanical environment.

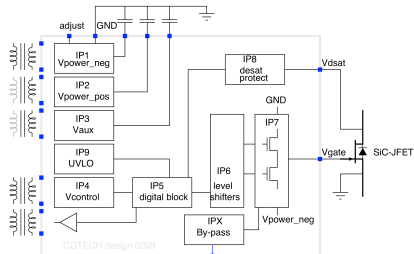


Figure 9: Schematic of a SOI driver [55]

4.4 WBG converter

Now that some SiC components have become available, some of the research work has shifted to high-temperature converters. As it is discussed here, active devices are just one of the many parts required to build a converter (high temperature passive, packaging, control circuits are also required). As long as the ambient temperature remains under 150°C, classical silicon control circuits can be used.

This is the case with inverters designed for automotive hybrids, which make use of the ICE cooling loop (120°C). In this case, it is possible to use Si-IGBTs together with SiC-SBDs, providing that the thermal resistance of the package is low enough to keep the junction temperature of the IGBT below 175°C. In [56], an inverter operating at 150°C ambient temperature is presented. The idea is to

take advantage of SiC devices to allow the junction temperature to reach 250°C. A 100°C temperature gradient allows to use a less efficient (and therefore much smaller) heat-sink

At an even higher temperature (200°C), a SiC MOSFET-based, 2kW boost converter is demonstrated in [57].

In [58] authors have designed all the basic building blocks for a JFET driver, to be built in SOI. These blocks (in discrete form) have been used to drive a JFET-based inverter operating at 200°C ambient temperature [59]. Figure 10 pictures the inverter. This converter uses high-temperature ceramic capacitors as the DC input filter and a hermetic package for the power module, both mounted on a polyimide board using a lead-rich solder alloy. The dies of the module are bonded using Au-Ge high temperature solder (melting temperature 356°C [60]).

Finally in [61] a buck converter (SiC-JFET and SiC-SBD) is tested at 400°C. However, due to the very high leakage current in the SBD at high temperature, the converter is down-rated to 200V instead of 600V. Moreover the saturation current in the SiC-JFET drops from 3.5A to 0.7A at high temperature. Commercially available SiC-JFETs by SiCED already offer better performances. Also some components such as the control circuits and the input capacitor are kept at ambient temperature.



Figure 10: A JFET-based, 540 V, 15 A, 3-phase inverter in a single package with an external DC capacitor.

5. Conclusion

The paper has discussed the now priority issues for the integration of high-temperature power converters. Power devices are key enablers and GaN and SiC devices have been demonstrated. In parallel a large effort has to be dedicated for the development of passive components and probably the capacitor suffers more limitations than the magnetic counterparts. The integration of the control of the converter is addressed at 2 levels: SOI-CMOS drivers are experimented and GaN and SiC equivalent will be soon available. Digital electronics is also addressed, mostly with SOI technology but

GaN is largely possible and SiC will probably come later.

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Technologies	Max. Voltage	tan(δ)	C max. @1kV	Temperatures	$\Delta C/C$ (%) @ 200°C	Cost (x/5)	Reliability (x/5)	Maturity (x/5)
Ceramics, Class I, NP0/C0G	>qlq kV	<1%	<200nF	-55°C/250°C	<2%	4	3	4
Ceramics, Class II, X7R, X8R, BX..	>qlq kV	<3%	<10 μ F	-55°C/200°C	>50%	5	2	3
Films, PPS	>1kV	<3%	<5 μ F	-55°C/175°C	<2%	3	4	2
Films, PTFE	<1kV	<3%	<1 μ F	-55°C/200°C	<3%	5	4	5
Films, Mica HT°	>qlq kV	<3%	<100nF	-55°C/250°C	<1%	3	5	5
Films, PEEK	<1kV	NA	NA	-55°C/200°C	NA	3	NA	1
Films, PEI	<1kV	NA	<5 μ F	-55°C/180°C	NA	2	NA	2
Solid Electrolytic, Tantalum	<100V	NA	<100nF @ 100V	-55°C/200°C	>20%	3	3	5

Table 1. Comparison of high temperature capacitor technologies (NA: Non Advised)

Alloys	Permeability	Sat. Flux Density	Coercive Field	Curie Temperature	$\Delta\mu/\mu_i$ (%) @ 200°C	Cost (x/5)
Ferrites (MnZn, NiZn)	60 – 2000	0.3 – 0.45T	10 – 100 A/m	280 – 400°C	< \pm 50%	2
Powder cores (Fe, FeNi, FeNiMo, FeSi, FeSiAl)	20 – 500	0.75 – 1.6T	20 – 100 A/m	460 – 550°C	< 10%	2 to 5
Amorphous ribbons (Fe, FeCo, FeNi)	1000 – 100000	0.6 – 1.2T	1 – 10 A/m	365 – 485°C	< 50%	3 to 5
Nanocrystalline ribbons (FeCuNbSiB)	200 – 100000	1.2T	1 – 10 A/m	< 570°C	< 50%	2 to 4

Table 2. Comparison of “high temperature” magnetic materials.