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Higher temperature power electronics for larger-scale mechatronic integration

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Abstract: Higher temperature electronics is driving large development efforts regarding many issues, especially the objective of integration. The main targets 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 the state of the art and results contributed by Ampere-lab.

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

1. Introduction

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

Even when considering “classical” vehicles (as opposed to hybrid or full electric cars), the cost of the electrical system is higher than the internal combustion engine (ICE) cost, 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]). In 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 a small margin when working with 150°C or 175°C-limited silicon devices. New wide band gap materials, such as Silicon Carbide (SiC) or Gallium Nitride (GaN), 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. Consequently, some converters will be subject to harsh environment. For example, some of them will have to operate nearby the jet engine, with ambient temperature ranging from -55°C to 225°C [4].

Obviously very high reliability is expected from these systems, in spite of long operating life (10 - 30 years) and 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 “higher 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 on power density [5]

Fig.1 in [5] pictures the possible integration offered by wide band-gap (WBG) devices: the power density is increased 10 times. 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.

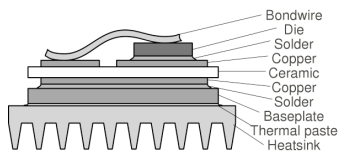


Figure 2: Schematic of a power module assembly

2. Packaging and Interconnection

Most packaging solutions have been developed for mild ambient [7], and a complete redesign is required for 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 are submitted to an ambient temperature that ranges from -55 to 225°C [4]. As presented 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 expand differently (due to different coefficients of thermal expansion), creating stresses at the interfaces. During the life of the power module, a 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 additionally, the melting point of the solder must be low enough to prevent any damage 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 are the mechanical properties of the solder alloy. This is defined by a ratio, called the homologous temperature, defined as $T_h = T_o[K] / T_M[K]$

where T_o and T_M are respectively the maximum operating and melting temperatures. It is considered that the mechanical properties of a material are degraded above $T_h=0.5$ [10], although values as high as 0.85 are usual in electronics.

For High Temperature applications, T_o 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_o further, the soldering alloy has to be replaced by a new composition. To avoid the race between T_o and T_M , alternatives solutions are being evaluated.

2.2 Alternative solutions for interconnexion

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].

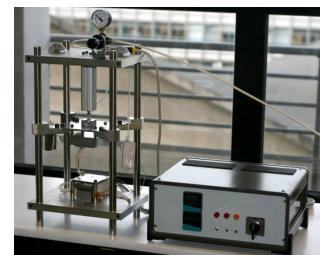


Figure 3: Heating press developed at Ampere-lab for the die attach operation

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). It makes this solution difficult to implement. The advantages of this solution are: a good bonding in air atmosphere

and no organic materials involved (if pre-forms are used). That is considered as a “clean process”,

3. Passive devices

3.1 Capacitors

Higher temperature capacitor technologies are based on the different dielectrics listed in the Table 1 and presented in 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 (typically 1kV-5 μ F), performances of dielectric films (PPS-based) and High-K ceramics are quite similar until 150°C/175°C.

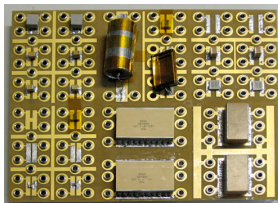


Figure 4: Testboard for high-temp characterization of passive devices

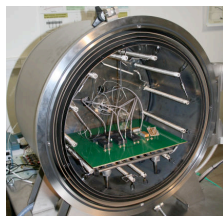


Figure 5: Experimental setup for high-temp characterization

Films are lighter but more bulky, and 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 behaviour with the temperature and the polarization [20, 21, 22]. For instance, X7R's capacitance decreases up to 60% with combined

high DC-bias voltage and 200°C-ambient temperature. 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 issues 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 good properties at 200°C. Losses are not affected by the temperature but the permeability decreases.

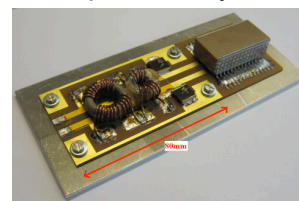


Figure 6: Discrete filter module for high-temp operation

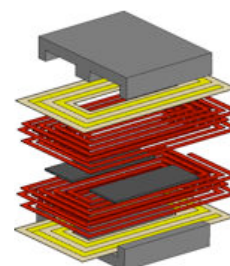


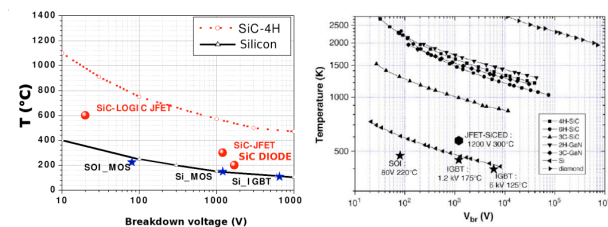
Figure 7: Schematic of integrated planar filter

Few years ago, the permeability range was extended to low permeability, about 200, and these materials are becoming industrialized [25]. Then, the nanocrystalline materials cover all power electronics

needs, typically boost inductor, line inductor, CM choke [26] or Flyback transformer. Core geometries are limited to a toroid, C or U cores and cores smaller than a centimetre 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 for passives

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 PCB integration but capacitance values will be low as well as thermal conductivity. For magnetic devices, limitations are mainly packaging, especially for powder cores and nano-crystalline ribbons but powder cores and ferrites could be moulded with 3D geometries. Fe-Amorphous ribbons are much less brittle than nano-crystalline ribbons with lower performances. However, performances are better than ferrite ones, and planar core structure could be considered for power inductor or transformer in the mid-power range (1-10kW).



other substrates such as silicon, silicon carbide or sapphire (Al₂O₃) [28]. The main limitations for sapphire are the mismatches of the lattice structures that induce many crystal defects in GaN, and the low thermal conductivity [29]. Silicon carbide is a good candidate because their properties are close to GaN. However, SiC is 100 times more expensive than silicon, consequently it is not economically viable today [30]. The third candidate is the silicon: the main advantages are the maturity and the availability of the process. 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 process which is compatible to be run on a standard CMOS line [31]. However, GaN does not have a native oxide unlike Si nor SiC. More studies are in progress to find a suitable a reliable oxide making GaN-MOSFET realistic [32].

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

4.2 GaN devices

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

Different structures have been explored for vertical power device. Toyota explores vertical structures such as AlGaIn/GaN HFET or UMISFET, but these structures have low breakdown voltage, respectively 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 the heterostructure at the interface of AlGaIn and GaN materials. A 2D gas of electrons enables to obtain very high mobility in the device. The quasi-absence of holes in GaN HFET structure eliminates the minority carrier effect in reverse recovery charge, and thus reduces 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 using a 4in Si-wafer with AlGaIn epitaxial layer [38]. The GaN-based LED market need will probably lead to a significant cost reduction in 4in GaN epi-wafer [Fig. 10]. Today, this point has to be considered to compare GaN and SiC devices.

4.3 GaN integrated circuits

The main constrains to design GaN-ICs, as well as SiC-ICs, is that P-type transistors are neither available nor reliable MOSFETs. Digital and analog functions have been developed especially for RF applications [39]. They are based on the Direct-Coupled FET Logic (DCFL) (as well as for SiC). GaN technology is more sensitive to temperature than SiC one. The most advanced GaN-IC is a 3-stage amplifier presenting a 22dB gain at 26GHz [40].

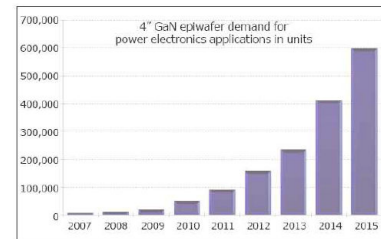


Figure 10: Unit forecast for 4in GaN epiwafers [YOLE 2010]

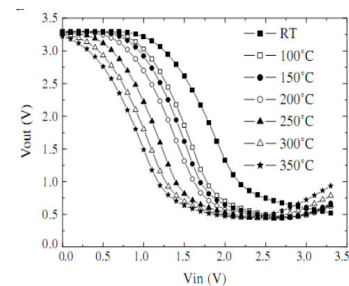


Figure 11: Static transfer function of the 3-stage amplifier in [40]

4.4 Silicon-Carbide devices

SiC power devices have been demonstrated and probably the SiC-MOSFETs and SiC-IGBTs are the expected 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 research teams are now focusing on the achievement of reliable and efficient compact integrated systems, composed of both power and control parts. Concerning the control circuit, analog functions (amplifiers, comparators, clocks) are able to operate more than 6000 hrs at 500°C without significant degradations [42]. Gate drivers [43, 44] and control circuit [45] have been successfully tested at 300°C. More recently, smartpower application benefits have been illustrated in [46, 47], and a fully integrated boost converter has been fabricated [48]. Building blocks (clock generation, voltage reference, thermal protection) have been demonstrated at Ampere-lab (Fig. 12). A hybrid demonstration of a SiC-MESFET-based flyback converter showed the feasibility to fabricate a fully integrated compact AC/DC converter.

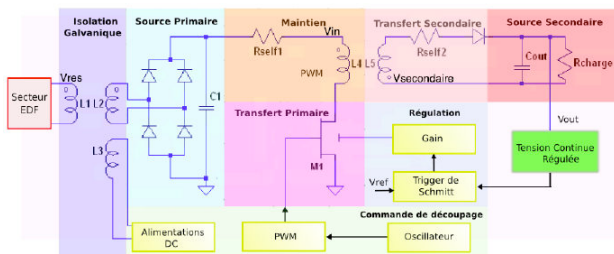


Figure 12: Schematic of a fully integrated AC/DC converter

Both NMOS, CMOS and JFET/MESFETs based-logic have been implemented and their high-temperature operation capabilities have been investigated. Despite its normally-on drawback, the JFET/MESFET technology is the most stable one for high temperature because SiC-MOSFET is suffering from its 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 they are subjected to the relaxation phenomenon (loss of data after 11-day operation 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 guarantee a long-term reliability.

4.5 CMOS SOI Drivers

Most of high temperature converters use control circuits made on 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]. A year at 300°C has also been reported using a technology which was available in 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 Cissoïd Company also designs 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 the EMI level is high and the power consumption not acceptable. A similar coreless isolation option is experimented by ROHMS. An impressive isolation level (2500V, 75kV/μs) is obtained at the penalty of an increased EMI source. Ampere-lab is participating to many projects (SEFORA, COTECH, THOR) devoted to SOI-driver development (240°C, Fig. 13). 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 relative permeability (100000 at ambient T° but a decrease of 50% à 220°C). The immunity to dV/dt is decreased by the stray common-mode capacitances. 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 only if high Curie-point ceramics can be manufactured and provide a tolerable mechanical environment.

4.4 WBG converter

As some SiC devices have become available, some studies have shifted to higher-temperature converters. As mentioned in this paper, active devices are just one of the many parts required to build a converter (higher 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.

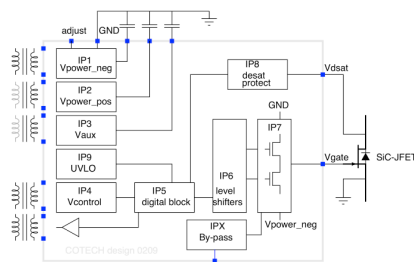


Figure 13: Schematic of a SOI driver [55]

This is the case with inverters designed for automotive hybrids, which are using of the ICE cooling loop (120°C). In this case, it is possible to use Si-IGBTs together with SiC-SBDs. The thermal resistance of the package is kept low enough to ensure the junction temperature of the IGBT is 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 using a less efficient (and therefore much smaller) heat-sink.

At a 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 (fig. 13). These blocks (in discrete form) have been used to drive a JFET-based inverter operating at 200°C ambient temperature [59]. Fig. 14 pictures the inverter. This converter uses high-temperature ceramic capacitors as DC-link capacitance, 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. In addition, some components such as the control circuits and the input capacitor are kept at ambient temperature.

5. Conclusion

The paper has discussed the main issues for the integration of high-temperature power converters

today. Power devices are the key enablers, and GaN and SiC devices have been demonstrated.

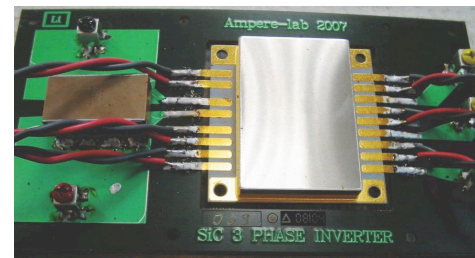


Figure 14: A JFET-based, 540 V, 15 A, 3-phase inverter in a single package with an external DC capacitor.

In parallel a large effort has to be dedicated for the development of the 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, however GaN offers large possibilities, 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.