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Review of semiconductor devices and other power electronics components at cryogenic temperature

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ABSTRACT

With the increasing demand for high power density, and to meet extreme working conditions, research has been focused on investigating the performance of power electronics devices at cryogenic temperatures. The aim of this paper is to review the performance of power semiconductor devices, passive components, gate drivers, sensors, and eventually power electronics converters at cryogenic temperatures. By comparing the physical properties of semiconductor materials and the electrical performance of commercial power semiconductor devices, silicon carbide switches show obvious disadvantages due to the increased on-resistance and switching time at cryogenic temperature. In contrast, silicon and gallium nitride devices exhibit improved performance when temperature is decreased. The performance ceiling of power semiconductor devices can be influenced by gate drivers, within which the commercial alternatives show deteriorated performance at cryogenic temperature compared to room temperature. Moreover, options for voltage and current sense in cryogenic environments are justified. Based on the cryogenic performance of the various components afore-discussed, this paper ends by presenting an overview of the published converter, which are either partially or fully tested in a cryogenic environment.

KEYWORDS

Cryogenic, power electronics, metal–oxide–semiconductor field-effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT), gate driver.

Power electronics play an essential role in modern electrical power conversion. In extreme cases, such as space exploration or particle accelerators, power electronics devices and circuits must withstand cryogenic temperature.

With the development of wide bandgap devices, next generation devices are expected to operate at higher power densities than traditional silicon (Si) devices owing to the high breakdown field of silicon carbide (SiC) and gallium nitride (GaN)[1]. Besides, wide bandgap devices have potentially the ability to switch faster and conduct current more efficiently than Si counterparts[2]. However, this prevalent view of power semiconductor devices is inaccurate at cryogenic temperatures. Physical properties of semiconductor materials change vastly when temperature decreases. So do the electrical performance of commercial power semiconductor devices.

After this introduction, Section 1 of this article reviews the effects of low temperature on different power semiconductor devices including diodes, metal–oxide–semiconductor field-effect transistors (MOSFETs), High-electron mobility transistors (HEMTs) and Si insulated-gate bipolar transistors (IGBTs). Section 2 moves on towards the cryogenic performance of passive components, i.e., capacitors, magnetic components, and resistors. Section 3 is devoted to the published works of cryogenic gate drivers, voltage and current sensing options, and converter systems tested in cryogenic. Finally, Section 4 concludes this paper.

1 Power semiconductor devices

In this section, diodes, MOSFETs, IGBTs are compared at low temperatures. In cryogenic temperatures, the test circuit and methodology are the same as those at room temperatures. Figure 1 shows the averaged performance drift when the temperature is reduced from room temperature, which is around 300 K, to a cryogenic temperature of 77 K. It should be noted that the actual junction temperature can be significantly higher than ambient temperature, heat sink temperature, or even the temperature of the case. At room temperature (RT), the junction temperature is often as high as 125 °C or even 150 °C. Therefore, even if the device is cooled by liquid nitrogen, the junction temperature is maybe 100 K or 150 K. However, for the sake of simplicity, we should stay with the comparison of 300 K and 77 K.

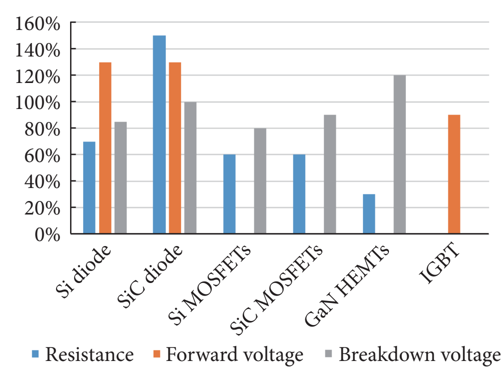

Figure 1 Comparison of semiconductor devices' average performance at cryogenic temperatures with these characterizations at room temperatures.

1.1 Materials for power semiconductor devices

Si semiconductor technology has reached a high level of maturity. In the meantime, the demands for high power density and high

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operating frequency have been driving research towards wide band-gap semiconductor materials since the 1990s. Before analysing the various semiconductor devices, it is necessary to know how the physical properties of semiconductor materials change at cryogenic temperature. Table 1 shows the differences in various physical properties bandgap E_g, electron mobility μ_v, saturation velocity v_{sat}, thermal conductivity k and critical field E_{cr} at room temperature (RT) and cryogenic temperature (CT)[2–13].

Table 1 Comparisons for physical properties in different temperatures

	Si		SiC		GaN	
	300 K	77 K	300 K	77 K	300 K	77 K
E_g (eV)	1.126[6]	1.167[6]	3.23[10]	3.27[10]	3.4[3]	3.48[3]
μ_v $(cm^2 \cdot V^{-1} \cdot s^{-1})$	650 @ $N_d = 2\times10^{17} cm^{-3}$ [7]	≈1000 @ $N_d = 2\times10^{17} cm^{-3}$ [7]	100[13] 35[12]	600[13] 18[12]	1067[2]	2885[2]
v_{sat} $(10^7 cm \cdot s^{-1})$	0.96[8]	1.3[8]	2[4]	Not found	0.9[5]	1.3[5]
k $(W \cdot m^{-1} \cdot K^{-1})$	76[9]	> 240[9]	66[11]	85[11]	100 ~ 200[1]	200 ~ 1000[1]
E_{cr} $(MV \cdot cm^{-1})$	0.25[4]	Not found	3[4]	Not found	4[4]	Not found

Given the same type of semiconductor devices made with the same material, higher electron mobility means more opportunities and possibilities to minimize the resistances[14]. In general, the value of electron mobility can have a large difference with different doping concentrations and the thicknesses of semiconductor layer[13]. As the temperature decreases to 77 K, the electron mobility can increase to at least twice that at room temperature for all the three semiconductor materials[2, 7, 13]. Specially, even if 4H-SiC and 6H-SiC shows monotonically increasing electron mobility when the temperature decreases from room temperature (300 K) to cryogenic temperature (77 K)[15], the electron mobility decreases greatly from 500 K to 300 K[16] and from 450 K to less than 100 K[12] for 4H-SiC MOSFETs. The reason for this phenomenon, can be carbon defects under this low temperature condition[17].

In addition to electron mobility, the variation of band gap, critical field, thermal conductivity, and saturation velocity with temperature fluctuations also can impact essential device parameters, e.g., breakdown voltage and on-resistance. The saturation and thermal conductivity show a monotonically increasing trend with the temperature decreasing to CT[5–11].

With the reduction of the temperature to 77 K, the bandgaps of Si, SiC and GaN slightly enhance by 1%–5% of these at RT [3,6,10].

1.2 Diodes

1.2.1 Silicon and silicon carbide diodes

Si and SiC diodes are widely used in high switching frequencies circuits. In contrast to SiC substrate, Si diode demonstrates a greater advantage at cryogenic temperature with lower on-resistance than room temperature. Figure 2 shows the normalised on-resistance of Si and SiC diodes[18–20]. The resistance of Si diodes declines in CT because the electron mobility is larger in this temperature, as shown in Table 1. Because of the stable atomic configurations and energy levels of carbon defects in silicon carbide and silicon dioxide, especially at low temperatures, SiC devices suffer from the unexpectedly low electron mobility[17, 18], which can be a possible reason for the increased on-resistance of SiC diodes at lower temperature.

Figure 3 shows the comparison of normalised breakdown voltage of Si and SiC diodes[18–20]. Compared to SiC diodes, the breakdown voltage of Si diodes normally declines at CT. It is noteworthy that, Refs. [18] and [19] test the same Schottky rectifier diode MBRS360TR, but have slightly different results, with +5% and −17% for the breakdown voltage in CT compared with RT. Due to lack of details of topology and test methodology, it is difficult to discuss the possible reason for these different results.

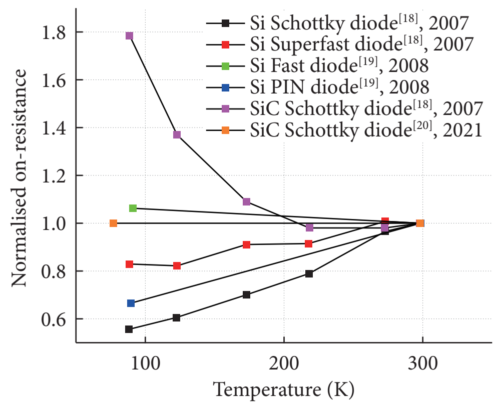

Figure 2 Normalised on-resistance of Si and SiC diodes.

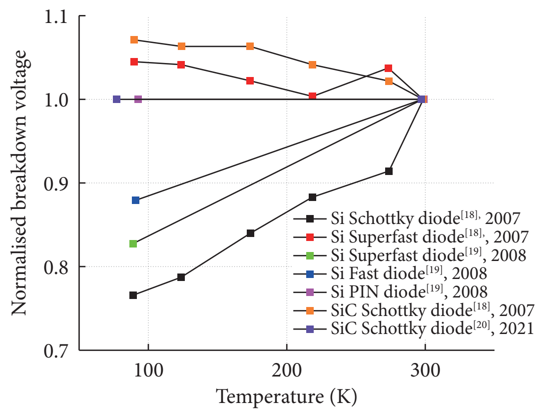

Figure 3 Normalised breakdown voltage of Si and SiC diodes.

For both Si and SiC diodes, the forward voltage in lower temperature is much larger than that in room temperature. Figure 4 shows the normalised forward voltage in different temperatures[18–24]. Most diodes, no matter whether Si or SiC, the forward voltage will increase 10% to 80% when the temperature declines from 300 K to less than 100 K, because the intrinsic carrier concentration can decrease during this progress.

1.2.2 Gallium nitride diode

As a wide bandgap material with higher breakdown field, GaN brings about possibilities for lower on-resistance of semiconductor devices in same power rating than traditional Si semiconductors. In Refs. [25] and [26], two GaN diodes with different constructions were tested in cryogenic temperature. Figure 5 shows the nor-

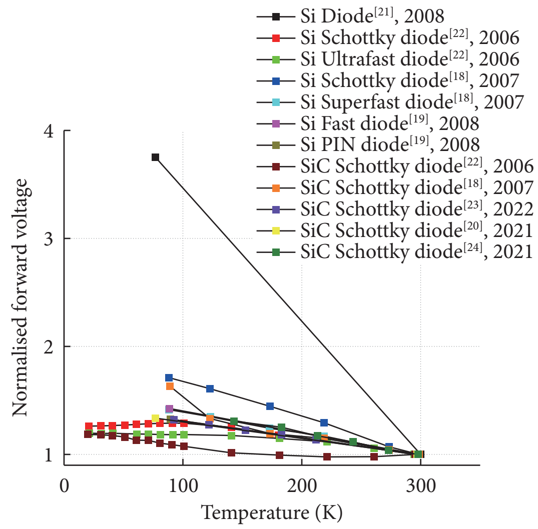

Figure 4 **Normalised forward voltage of Si and SiC diodes.**

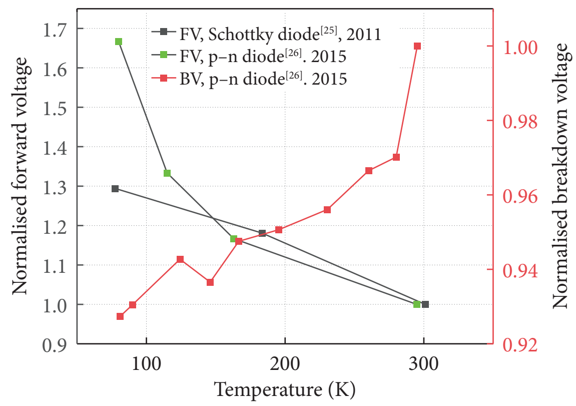

Figure 5 **Normalised forward voltage and breakdown voltage of GaN diodes.**

malised forward voltage and breakdown voltage of GaN diodes[25,26]. These two characteristics of GaN didoes show the same trend as the Si and SiC diodes when temperature declines, with lower breakdown voltage and higher forward voltage in CT, as also shown in Figure 6.

However, due to the different constructions and different higher-doped layers, the on-resistance for these two diodes show a opposite result at CT. In the p–n diode process in Ref. [26], 0.5 μm layer doped with Mg for reduced contact resistance. However, Mg doping layer can cause freeze-out effect, which will decrease electron and hole concentrations as the temperature is reduced. Consequently, with decreasing temperature, the turn-on voltage increases by 560%[26]. The on-resistance of Schottky diodes in Ref. [25] decreases slightly by 8% at CT when compared to RT, because the Schottky barrier height (SRT) region will change at low temperature.

1.2.3 Summary

In summary, the Si diode shows better performance at low temperature than SiC devices, with much lower on-resistance , as shown in Table 2[21–26]. As a highly anticipated wide-bandgap semiconductor material, GaN diodes are currently unavailable and suffer from poor performance at any temperature[26]. For all the three types of diodes, the forward voltage is much higher at cryogenic temperature than that at room temperature, because the intrinsic carrier concentration has positive temperature coefficient.

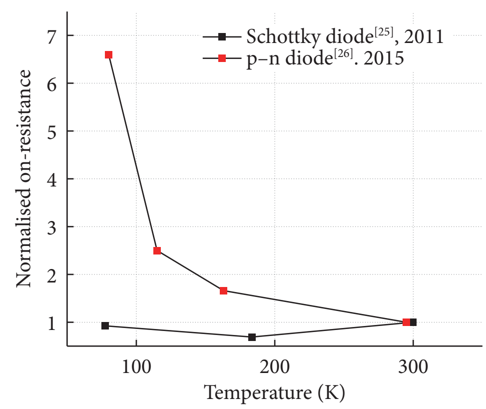

Figure 6 **Normalised on-resistance of GaN diodes.**

Table 2 **Summary of diode comparison**

Device	Material	Rated voltage (V)	Test result in cryogenic temperature compared with room temperature		
			Forward voltage	On-resistance	Breakdown voltage
Diode (Not specified)[21]		Not specified	+275%	N/A	N/A
MBR20200CT, Schottky diode[22]		200	+29%	N/A	N/A
MUR1560, Ultra-fast diode[22]		600	+18%	N/A	N/A
MBRS360TR, Schottky rectifier diode[18, 19]	Silicon	60	+71%	−44%	−33%
ES2A, Super-fast rectifier diode[18, 19]		50	+41%	−17%	+5%[18] −17%[19]
1N4148, fast-switching diode[19]		100	+43%	+6%	−12%
Bap64-04w, PIN diode[19]		100	+33%	−33%	0%
CSDI0060, Schottky diode[22]		600	+10%	N/A	N/A
CSD10030, Schottky diode[18]		300	+63%	+79%	+7%
C3D08065, Schottky diode[23]	Slicon carbide	650	+32%	N/A	N/A
GB2X100MPS12-227, Schottky diode[20]		1200	+34%	+50%	0%
Schottky diode (Not specified)[24]		Not specified	+30%	N/A	N/A
Schottky diode (Not specified)[25]	Gallium nitride	600	+29%	−8%	N/A
p-n diodes (Not specified)[26]		1200	+67%	+560%	−7%

The breakdown voltage shows a downward trend when temperature deceases to less than 100 K. The setup topology and the test methodology can affect this result slightly. Besides, according to the results in Ref. [22], the silicon diodes MBR20200CT and MUR1560 exhibit a significant reduction in the switching loss at low temperatures with lower diode reverse recovery time. It is worth noting that in some converters, diodes operate alternate with other self-commutated semiconductor devices, which put the switching losses for diodes in an important place, even though very few papers mention diode losses at cryogenic temperatures.

1.3 MOSFETs

1.3.1 Si MOSFETs

Si MOSFET is a semiconductor device commonly used in high frequency applications with lower voltage than silicon IGBTs. Besides, with the development of super-junction (SJ), such as CoolMOS family from Infineon, Si MOSFET has gained great competitiveness over wide band-gap counterparts in reducing the power loss in low voltage applications at lower cost.

The resistivity $\rho(T)$ of the drift region is related to both the temperature dependent free carrier concentration $n(T)$ and the electron mobility $\mu_n(T)$[27]:

$$\rho(T) = \frac{1}{q\mu_n(T)n(T)}$$

With a temperature decrease down to cryogenic temperature, the increased electron mobility μ_n will cause the resistance of Si MOSFETs to decrease.

Figure 7 shows the on-resistance for different types of SJ MOSFETs[20,27]. When the temperature decreases down to the range between 50 K and 100 K, the devices under test reach their absolute minimum on-resistance due to the increased electron mobility. However, if the environmental temperature keeps reducing down to 20 K, the carrier freeze-out effect dominates, and the on-resistance increase[27].

The breakdown voltage of the Si MOSFETs presents a temperature drift similar to that of the Si diode. As shown in Figure 8[20,27,28], the breakdown voltage of the Si MOSFETs can decline by 15% ~ 35% when temperature is reduced from CT to RT. Differently, the Si MOSFETs show 25% increase in the gate-source threshold voltage at CT due to the 30 orders of magnitude fall in the intrinsic carrier concentration from 300 K to 77 K[28].

1.3.2 SiC MOSFETs

SiC MOSFETs are regarded as an option for high temperature applications due to their lower leakage current when compared to Si counterparts. However, as shown in Figure 9[29,30], the on-resistance of SiC MOSFETs increases more than 30% at CT compared to the RT value due to the freeze-out effect and the carbon defects at a SiC/SiO_2 interface[17].

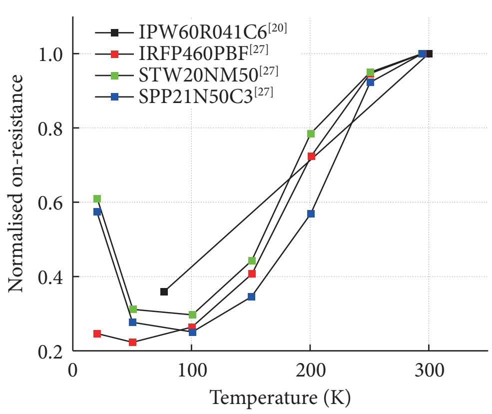

Figure 7 Normalised on-resistance of Si-SJ MOSFETs.

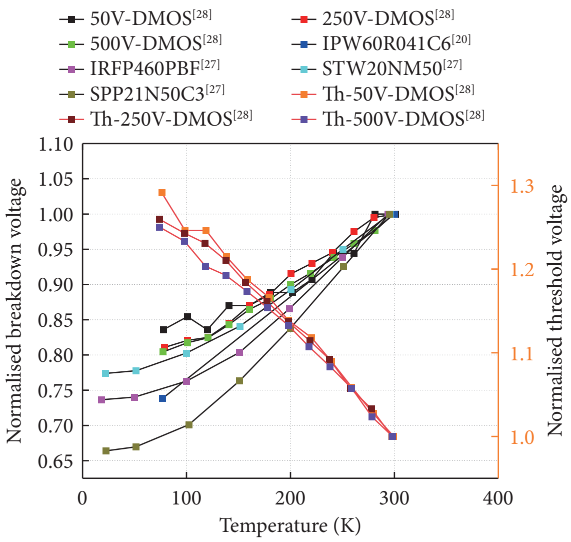

Figure 8 Normalised breakdown voltage and gate-source threshold voltage of Si MOSFETs.

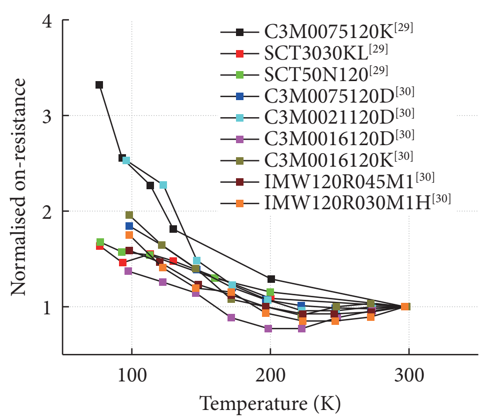

Figure 9 Normalised on-resistance of SiC MOSFETs.

Compared with Si MOSFETs, SiC MOSFETs have a better performance with respect to the breakdown voltage. As shown in Figure 10[29,30], the breakdown voltage of SiC MOSFETs only have 0% to 20% reduction at low temperature. The carrier freeze-out can be one possible reason for this observation. The reduced carrier amount mitigates the impact ionization and allows higher voltage across the drift region[29].

The gate-source threshold voltage trends are shown in Figure 11[29,30], which keeps decreasing when temperature increases from CT to RT. It can be seen that there are some slight differences between the different manufacturers for the threshold voltage increases.

Figures 12 and 13 show the voltage fall time and rise time of SiC MOSFETs by Infineon and Wolfspeed[30]. The fall time of devices shows a monotonically increasing trends when the temperature decreases down to 100 K. As for the rise time, two Infineon MOSFETs show a significantly larger increase rate than others, especially at the temperature range of between 100 K and 200 K, which is more than 100% greater than that at RT.

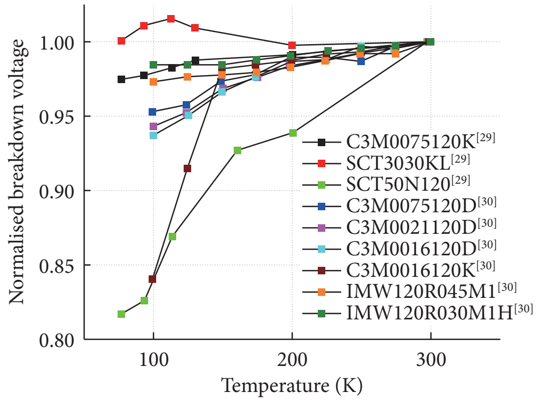

Figure 10 **Normalised breakdown voltage of SiC MOSFETs.**

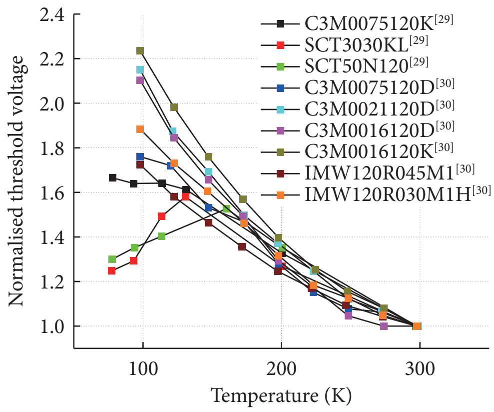

Figure 11 **Normalised gate-source threshold voltage of SiC MOSFETs.**

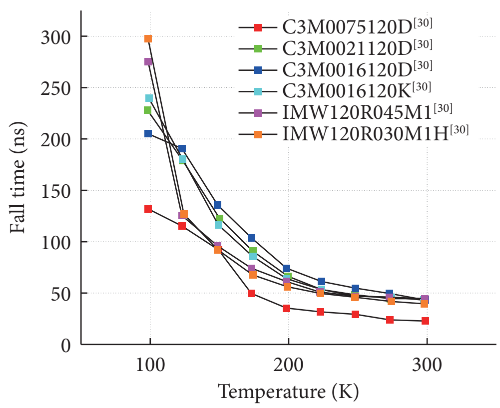

Figure 12 **Fall time of SiC MOSFETs.**

1.3.3 GaN HEMT

GaN HEMTs are another good candidate for wide bandgap device operating at cryogenic temperature, which have different semiconductor topology compared to Si and SiC MOSFETs. This is relatively a new technology and existing commercial GaN HEMTs device can achieve lower on-resistance at CT than the Si and SiC counterparts. Figure 14 plots the on-state resistance of GaN HEMTs at different temperatures[31–33]. The devices from manufacturers such as GaN Systems and efficient power conversion (EPC) demonstrate strong competitiveness at cryogenic temperature, which have less than 40% resistance at CT than at 300 K. The reason for the lower resistance at CT can be that the carrier density in the 2-dimensional electron gas (2DEG) at lower temperatures increases[33]. Moreover, the increasing electron mobility can be

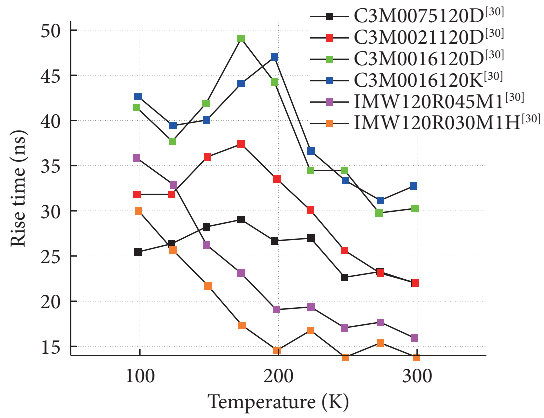

Figure 13 **Rise time of SiC MOSFETs.**

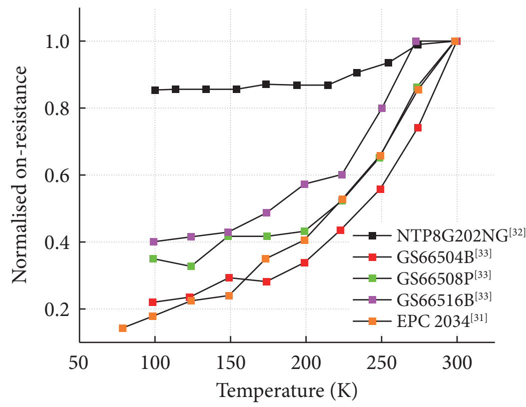

Figure 14 **Normalised on-resistance of GaN HEMTs.**

another boost for the declined resistance. The breakdown voltage of GaN HEMTs increases from 10% to 40% at CT as shown in Figure 15, which presents a negative temperature coefficient[33]. Therefore, GaN HEMTs out-perform Si and SiC MOSFETs in terms of the conduction loss and breakdown voltage.

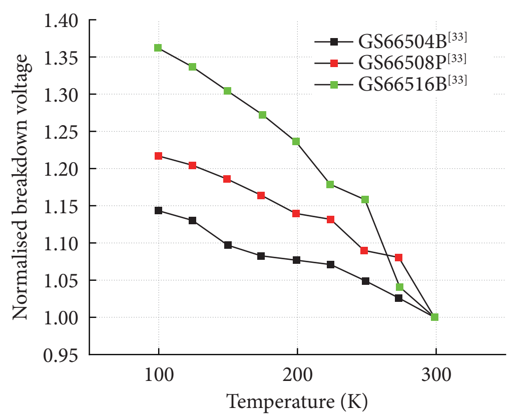

Figure 15 **Normalised breakdown voltage of GaN HEMTs.**

The gate-source threshold voltage of enhancement mode - HEMT devices have a negative temperature coefficient below room temperature according to the results shown in Figure 16[31,32]. Both devices from different manufacturers show, that the gate-source threshold voltage at CT increases by around 15% compared to RT. As the temperature of the device is lower, the gate bulk work function drops and the depletion charge also increases, therefore, the gate-source threshold voltage increases[32]. In Refs.

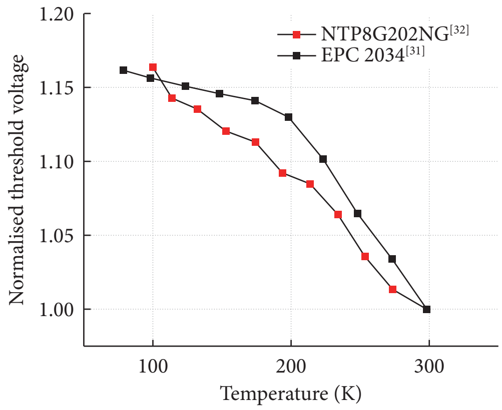

Figure 16 Normalised gate-source threshold voltage of GaN HEMTs.

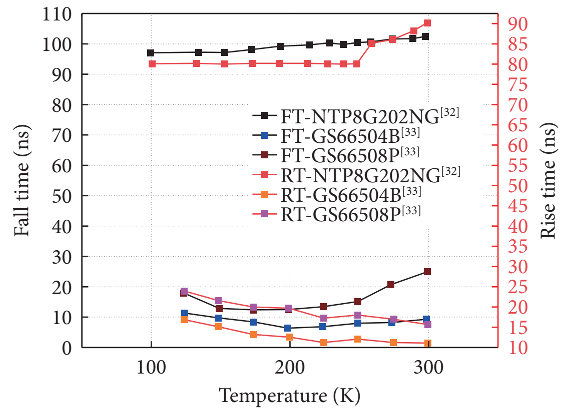

Figure 17 Switching time of GaN HEMTs.

[33] and [34], the researchers tested four types of GaN enhancement mode HEMTs from GaN Systems. Their work demonstrates confusing relevance between gate-source threshold voltage and temperature in these tests, the gate-source threshold voltage can fluctuate between 1 V to 2 V when temperature decreases to 100 K. A possible reason can be the special construction of GaN HEMTs, which needs more investigation on the impact of the cryogenic environment on the gate-source threshold voltage[33].

Figure 17 presents the switching characteristics of GaN HEMTs at different temperatures[32,33]. Compared to SiC MOSFETs, the fall time and rise time do not have a significant increase at cold temperatures, and the switching time of NTP8G202NG even slightly declines when temperatures go down. This improvement of switching performance in low temperature can be caused by the reduced input capacitances C_{iss} and C_{rss}.

In the development process of the GaN HEMTs technology, there are still some issues which affect the stability during operation, such as the kink effect. The kink effect is an abrupt increase in the drain current at a certain drain voltage that provokes an increase in the output conductance[35–38]. As shown in Figure 18, when temperature decrease to around 260 K, kink starts to arise and become even larger in 200 K[35]. As the temperature continues to drop, the electron mobility increases due to the expected reduction of polar optical phonon scattering, so the drain current increases at 100 K[35]. In Ref. [39], a light exposure experiment presents the correlation between photon energies and kink effect. Ref. [39] suggests that the kink is cause by the ionization energy between 0.8 eV and 3.32 eV.

1.3.4 Summary

GaN HEMTs and Si MOSFETs show better performance than SiC devices at cryogenic temperature, as shown in Table 3[20,28–31].

Table 3 Summary of MOSFETs comparison

Device	Material	Rated voltage (V)	Results in CT compared with RT				
			On-resistance	Breakdown voltage	Gate source threshold voltage	Fall time	Rise time
50 V DMOSFET [28]	Silicon	50	N/A	−16%	+29%	N/A	N/A
250 V DMOSFET[28]		250	N/A	−19%	+26%	N/A	N/A
500 V DMOSFET[28]		500	N/A	−20%	+25%	N/A	N/A
IPW60R041C6[20]		650	−64%	−26%	N/A	N/A	N/A
IRFP460PBF[27]		500	−78%	−26%	N/A	N/A	N/A
STW20NM50[27]		550	−39%	−23%	N/A	N/A	N/A
SPP21N50C3[27]		560	−43%	−34%	N/A	N/A	N/A
C3M0075120K[29]	Silicon carbide	1200	+231%	−3%	+67%	N/A	N/A
SCT3030KL[29]		1200	+64%	0%	+25%	N/A	N/A
SCT50N120[29]		1200	+68%	−18%	+30%	N/A	N/A
C3M0075120D[30]		1200	+85%	−5%	+76%	+473%	+16%
C3M0021120D[30]		1200	+153%	−6%	+115%	+418%	+44%
C3M0016120D[30]		1200	+37%	−6%	+110%	+377%	+37%
C3M0016120K[30]		1200	+96%	−16%	+124%	+456%	+30%
IMW120R045M1[30]		1200	+59%	−3%	+72%	+525%	+125%
IMW120R030M1H[32]		1200	+75%	−2%	+88%	+661%	+117%
NTP8G202NG[32]	Gallium nitride	600	−15%	N/A	+18%	−5%	−11%
GS66504B[33]		650	−78%	+14%	N/A	+22%	+52%
GS66508P[33]		650	−65%	+22%	N/A	-28%	+53%
GS66516B[33]		650	−60%	+36%	N/A	N/A	N/A
EPC 2034[31]		200	−86%	N/A	+16%	N/A	N/A

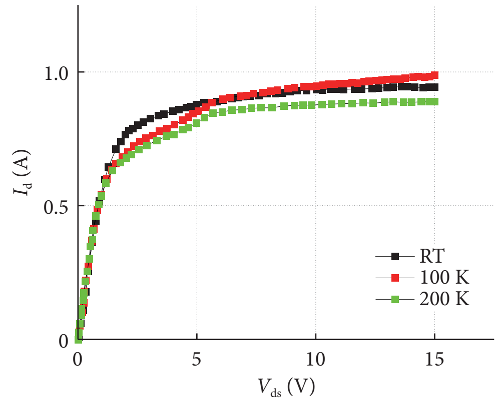

Figure 18 Kink effect in GaN HEMTs[35].

The switching time of SiC MOSFETs increases significantly at cryogenic temperature, so does the on-resistance. In contrast, the on-resistance of GaN and Si devices drops with falling temperature. In addition, the switching time of GaN HEMTs decreases with temperature, as input capacitances decrease. As a rapidly advancing wide bandgap device, GaN HEMTs show better performance at CT and more possibilities than all the other counterparts.

1.4 IGBTs

Compared to Si MOSFETs, Si IGBTs are considered to have lower forward voltage and lower cost in high voltage applications[40]. However, IGBTs have the disadvantages of a comparatively large current tail, which limits its applications at high-frequency switching[41]. As wide bandgap (WBG) devices continue to evolve, the status of traditional IGBTs in high power applications continues to be challenged.

The gate-source threshold voltage of IGBT, presented in Figure 19[40,42–45], shows an increasing trend when the temperature decreases down to below 100 K, as happens with MOSFETs. As shown in Figure 18, the threshold voltage of IGBTs increases by around 20% at CT.

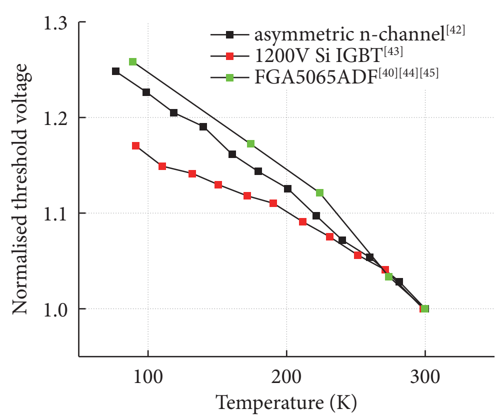

Figure 19 Normalised gate-source threshold voltage of IGBT.

As a voltage-controlled semiconductor device, the gate voltage can bring the IGBT into conduction, which are field-effect controlled. Once it is conductive, the voltage drops exhibits characteristics like MOSFETs, which called “MOSFET forward voltage drop” of IGBT in some papers. However, this expression may cause confusing in the article in which we compare IGBT and MOSFETs devices. So, in this article, this voltage drop is named as “Forward voltage drop” (V_f) of IGBT.

Figure 20 shows the knee voltage and the saturation voltage of an IGBT under different temperatures[40,42,44,45]. The knee voltage increases when the temperature decreases to below 100 K, which is caused by the reduction of the number of intrinsic carriers[44]. Due to the increase of the inversion layer mobility, the forward voltage and saturation voltage decreases at lower temperature[42]. However, when the temperature is further decreased, due to the carrier freeze out, the forward voltage drop for Si IGBT increases when the temperature is below 100 K.

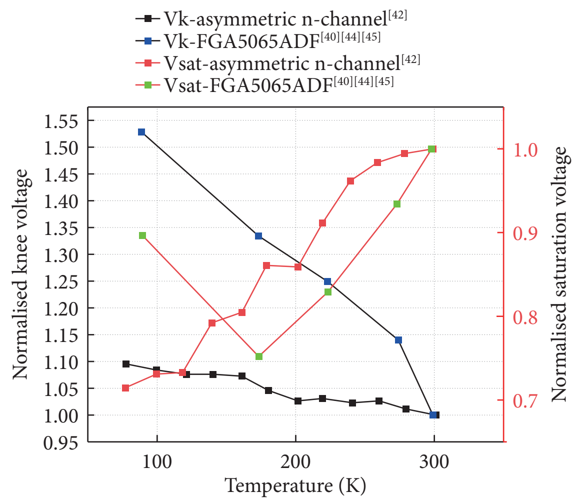

Figure 20 Normalised knee voltage and saturation voltage of IGBT.

In Ref. [42], the paper discussed the gain of the inherent PNP transistor of the IGBT, which decreases when temperature declines, and helps the current drop in the collector during the turn-off process at CT. As a result, the fall time of FGA5065ADF and IGW40T120 decrease by more than 30%. Figure 21 shows the fall time and rise time at the operating temperature, which support this theory[40,44,45].

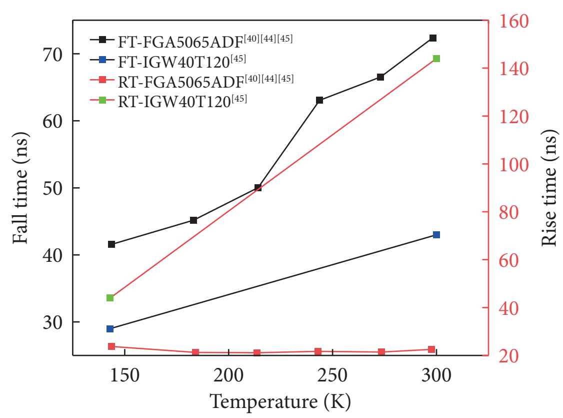

Figure 21 Fall time and rise time of IGBT.

In Table 4, with lower saturation voltage and the switching time decreasing at cryogenic temperature, IGBT presents a great competitiveness[42–45].

2 Passive components

2.1 Resistors

According to the test results in Refs. [18,19,41], the resistances for most types of resistors change only slightly with temperature. In

Ref. [41], the resistors were tested at a frequency of 1 kHz and thermally cycled for a total of five cycles. As shown in Figure 22, the resistances of both the carbon composition and ceramic composition are significantly increases at cryogenic temperature. Besides, the frequency has little effect on the resistance for all resistors tested[19]. However, depending on the cooling method, the same transistor at CT can have a higher power rating compared to RT (assuming the same temperature increase).

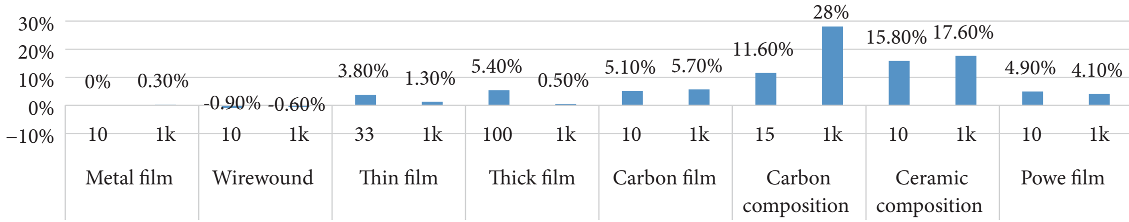

Figure 22 Resistance percentage increase at 83 K than 298 K[41].

Table 4 Summary of IGBT comparison

Device	Rated voltage (V)	Test voltage (V)	Test current (A)	Test result in CT compared with RT				
				Gate-source threshold voltage	Knee voltage	Saturation voltage	Fall time	Rise time
Asymmetric n-channel (Not specified)[42]	N/A	600	8	+25%	+10%	−29%	N/A	N/A
1200V Si IGBT[43]	1200	1200	N/A	+17%	N/A	N/A	N/A	N/A
FGA5065ADF[44,45]	N/A	650	650	+26%	+53%	−10%	−43%	+6%
IGW40T120[45]	1200	400	20	N/A	N/A	N/A	−33%	−70%

2.2 Capacitors

Most types of capacitors present little capacitance difference when tested with frequencies increasing from 1 kHz to 100 kHz. The polypropylene, polyethylene, NPO ceramic, and polyester capacitors showed a slight change in capacitance when they were cooled from room temperature to 77 K[46]. X7R and Z5U ceramic capacitors present a strong temperature dependence due to their ferroelectric nature[46], which resulted in a more than 60% decrease in the capacitance. Either aluminium electrolytic or tantalum electrolytic capacitors have dramatic reduction when the temperature drops to 77 K, or even complete failure, which is attributed to the freezing of the liquid electrolyte. Besides, tantalum material demonstrates a strong correlation between capacitance and frequency in Ref. [46] and Figure 23.

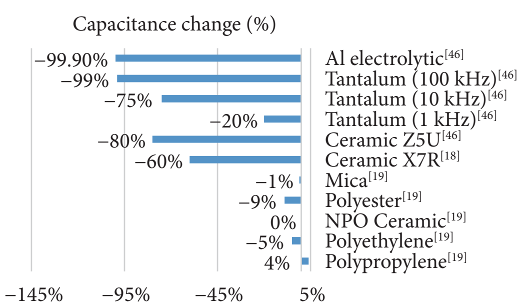

Figure 23 Capacitance percentage increase at 77 K than 293 K.

Another important factor for capacitors is reliability, because the repetitive cycling from RT to cryogenic temperatures can be damaging for most of the capacitor technologies. Some investigations have shown that larger devices (in volume) are especially prone to failure, but the literature still lack research on the reliability of capacitors at these low temperatures. It is necessary to ensure the reliability before using commercial capacitors at cryogenic temperatures, which includes research on thermal cycling and power cycling. Preliminary experimental results show that thermal cycling can cause mechanical stress due to materials' rapid expansion and contraction, potentially leading to delamination, cracking, or adhesive failures. These issues are critical in maintaining the integrity and performance of capacitors. Additionally, when these capacitors were soldered onto printed circuit boards, they sometimes showed watermarks, indicating potential condensation issues that could further compromise mechanical stability and reliability.

2.3 Inductors

2.3.1 Inductor magnetic cores

As an essential component of power electronics converters, the performance of inductors at CT has a great effect on the behaviour, efficiency, and power density of converters. Table 5 summarises the essential characteristics of the most common magnetic core materials at CT. Ferrite and supermalloy are very unsuitable for working at this low temperature since they exhibit a more than 85% drop in permeability. Besides, the device losses of ferrite core increase 90% at CT. Apart from these materials, powdered alloy materials in Table 5[47–50], specially powdered iron, moly permalloy, moly-prem and high flux cores, exhibit strong competitiveness with relative stable permeability at different temperatures. The core losses for nanocrystalline, amorphous non-oriented steel and grain-oriented steel are less than 15% for their different test frequencies, which make them good candidates for magnetic core materials at cryogenic temperatures.

2.3.2 Windings

The resistivity of five different winding materials have been tested at 270 K and 77 K, and all of them have positive temperature coefficient within this range, as shown in Table 6[51,52]. The resistivities of these wires decrease by more than 80% at 77 K compared to in 270 K. In high-frequency AC, eddy current losses due to the skin effect can be a significant source; Litz wires and copper-clad aluminium (CCA) can be used to combat these losses[52]. These two materials show great competitiveness with low resistivity at 77 K.

Table 5 Summary of magnetic core materials in CT

Material	Test frequency	Test results in CT compared with RT		
		Permeability	Saturation flux density	Core losses
Ferrite[47]	10 kHz	−90%	+36%	+90%
Nanocrystalline[47]	10 kHz	−20%	+11%	+5%
Amorphous[47]	1 kHz	−20%	+3%	+10%
Non-oriented steel[48]	10 Hz	−10%	+3%	+10%
Grain-oriented steel[48]	10 Hz	−10%	+2%	+11%
Supermalloy[49]	10 kHz	−86%	N/A	N/A
Powdered moly-prem[49]	10 kHz	−4%	N/A	N/A
Powdered permalloy[49]	10 kHz	−25%	N/A	N/A
Powdered iron[49]	10 kHz	−2%	N/A	N/A
Powdered moly permalloy[50]	100 kHz	−2%	N/A	N/A
Powdered high flux[50]	100 kHz	−7%	N/A	N/A

Table 6 Summary of winding in CT

Material	Resistivity in 77 K ($10^{-9}\Omega\cdot m$)	Change percent than RT
Copper[51, 52]	2.03	−88%
Ohno Continuous Cast Cu (>99.99998% pure)[52]	2.29	−88%
Litz Cu[52]	2.11	−87%
Al 1100 (>99% pure)[52]	3.10	−90%
CCA[52]	3.09	−88%

Compared to other materials, pure copper wire has the lowest resistivity at CT. Besides, copper-clad lithium (CuCLi) wires in Ref. [53] also show that the AC losses in the solid Cu wire increases significantly as compared to the CuCLi wire, when the frequencies increase from 400 Hz to 100 kHz. The reason for that is the special construction of one high resistance inter-metallic layer. Other materials, which are also not available commercially now, include extra high-purity aluminium and beryllium, show the possibility in the cryogenic temperature applications as well.

On the other hand, the heat dissipated from the wire's triggers vapour bubble formation and the boiling of surrounding liquid nitrogen[52]. The boiling regime and the bubbles can impede heat rejection. According to test results included in Ref. [52], 24 AWG copper wire with 0.2 mm^2 cross-sectional area has power dissipated around 61.9 W at 70 A at room temperature. However, submersed in liquid nitrogen (77 K), the power dissipated decreases to 9.07 W at 70 A, and the wire temperature reaches over 85 K.

3 Gate drivers, sensors and converters

3.1 Gate driver

Gate drivers bridge between the controller at RT and the power semiconductor at CT. Since they are required to charge and discharge the gate capacitance of the semiconductor very quickly and without over-/undershoot, they need to be placed very closely to the semiconductor to minimize the parasitic inductance. In practical applications, if the gate drivers and switching devices can be placed together in the same cold temperature, the whole circuit can have a lower noise and faster dynamic performances[54]. Consequently, there is necessary to discuss the performance of gate drivers in liquid nitrogen. The operating temperature of Si8271 from Silicon Lab can be as low as 93 K, when the output voltage set to 9 Volts[55]. However, at this temperature, the auxiliary power supply "MEJ2S0509SC" by Murata operating under light load condition, which cause the output voltage reach out of regulated voltage band based on the datasheet[55]. In Ref. [54], the same gate driver has been tested with 6 V output voltage and shows a more stable performance. ADuM4221 and UCC5304 produce a lower output voltage at cryogenic temperature than at room temperature, as shown in Table 7[55–58].

Six types of self-oscillating gate drivers are tested at both room and cryogenic temperature in Ref. [58]. However, there are only two of them that work at CT with lower switching frequency than at RT. L6571 from STMicroelectronics is functional up to 50 kHz, while the same value for FAN7387 is 100 kHz. For both gate drivers, the duty cycle decreased slightly when the temperature drops to 77 K.

Some commercial gate drivers demonstrate the potential to operate in liquid nitrogen or other low-temperature conditions, but most struggle to produce high signal quality compared to that at room temperature. The primary issues preventing their optimal performance at cryogenic temperatures include problems with the driver's DC/DC conversion stage and the isolation of the gate signal. The efficiency and stability of the DC/DC conversion stage can degrade significantly at cryogenic temperatures as components that perform well at room temperature may experience changes in their electrical properties, leading to reduced performance or failure. Additionally, cryogenic temperatures lead to signal integrity issues and potential driver circuit failures due to a compromised gate signal isolation.

Given these challenges, several research projects are now concentrating on developing partially cryogenic gate drivers. The concept involves designing a gate driver where the gate charging/discharging circuit operates at cryogenic temperatures while the rest of the system remains at room temperature (RT). This hybrid approach aims to leverage the benefits of cryogenic cooling for specific components while maintaining the reliability of the other components at RT[59].

3.2 Current sensors and voltage sensors

Current and voltage sensors are essential for monitoring and controlling the electrical parameters to ensure the efficient and safe operation of the power electronics converter in demanding environments. One of the primary challenges these sensors face is temperature-induced variations. Sensors that perform reliably at

Table 7 Gate drivers in CT

Part number		Manufacturer	Minimum working temperature	Performance in CT
Si8271[55, 54]		Silicon Lab	73 K	Overvoltage happens
UCC5304[55]		Texas Instrument	123 K	Output voltage decreases from 6 V to 5.6 V
UCC21540[54–57]			93 K	N/A
MAX22702[54]		Analog devices	130 K	N/A
Adum4221[54]			77 K	Output voltage decreases from 7.5 V to 6 V
Self-oscillating gate driver	L6571[58]	STMicroelectronics	77 K	Switching frequency decreases from 200 kHz to 50 kHz
	FAN7387[58]	On semiconductor	77 K	Switching frequency decreases from 650 kHz to 100 kHz

RT may exhibit significant deviations in their behaviour when exposed to cryogenic temperatures. These variations can affect their accuracy and responsiveness, which are critical for maintaining precise control in power circuits. Additionally, the materials used in the construction of these sensors can experience changes in their electrical and mechanical properties at low temperatures, such as shifts in resistance, capacitance, and magnetic properties. These changes can alter the performance of both current and voltage sensors. Another significant challenge is ensuring signal integrity across temperature gradients. Accurate signal transmission from the CT environment to the RT controller must be maintained without degradation, necessitating robust isolation and transmission techniques.

The performance of current sensors at cryogenic temperatures varies depending on their type and underlying technology. Shunt resistors can operate at low temperatures but may experience resistance drift[60]. Hall effect sensors are typically temperature-sensitive, as carrier mobility in semiconductors can change. However, some Hall sensors are specifically designed to operate at low temperatures[61]. Current transformers may require stable core materials. Rogowski coils, which are air-cored, typically perform well at cryogenic temperatures because they do not rely on magnetic cores prone to saturation or hysteresis effects. However, the coil's dimensions and material properties, including changes in inductance and capacitance due to temperature, must be carefully considered and calibrated for accurate current measurement[62].

Simple voltage divider circuits using resistors generally perform adequately if resistor stability and temperature coefficients are carefully managed. Zener diode sensors may experience shifts in their breakdown voltage due to semiconductor bandgap variations at low temperatures, necessitating specialized low-temperature diodes[55]. Voltage transformers, relying on magnetic cores and windings, require a careful selection of core materials to maintain stable magnetic properties. Capacitive sensors measure voltage based on capacitance changes, which can be affected by dielectric constant variations at cryogenic temperatures, requiring specific material choices. Piezoelectric sensors generate a voltage in response to mechanical stress, and their performance at cryogenic temperatures depends on the piezoelectric material used. Some materials exhibit reduced piezoelectric response at low temperatures, requiring careful selection for cryogenic applications.

3.3 Converters

Based on the comparisons of semiconductor switching and passive components at CT and RT, more different types of converters are designed and tested in both temperatures.

In Ref. [63], a bi-directional resonant converter as shown in Figure 24 is selected due to its soft switching capability a in wide frequency range. A cascode GaN FET (tp90h050s) were selected in this circuit, which has 900 V breakdown voltage at room temperature. The on resistance at CT decreases by around 40% that of RT, which is the same trend as the performance of the GaN devices as explained in a previous section. Gate driver Si8271 was used to drive the switching devices, which proved to work at 77 K temperatures. Besides, two types of capacitors were tested in this circuits. The capacitance of aluminium electrolytic capacitor decreases to around zero when temperature is lower than 213 K, which is the same as mentioned before. And polypropylene film capacitors show a stable performance when the temperature changes, which was finally used in both input and output circuits. When the output power is equal to 150 W, as shown in Figure 25, the efficiency changes are not obvious with temperature decreasing to cryogenic temperature. When the power rises to 400 W, the efficiency shows a slight decrease at 150 K, which can be caused by higher switching loss of GaN devices at cryogenic temperatures, or higher magnetic core loss.

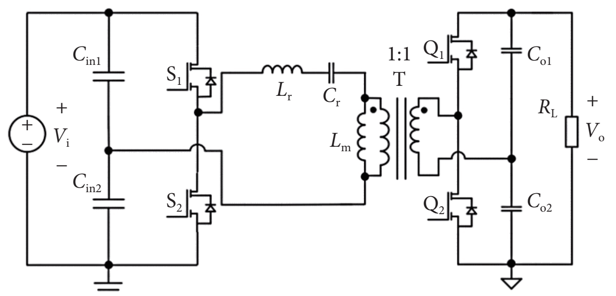

Figure 24 Bi-directional resonant converter. Reprinted with permission from Ref [63], © 2022, IEEJ.

A DC-DC boost converter and its individual components performances have been tested at 300 K and 77 K in Ref. [64]. As

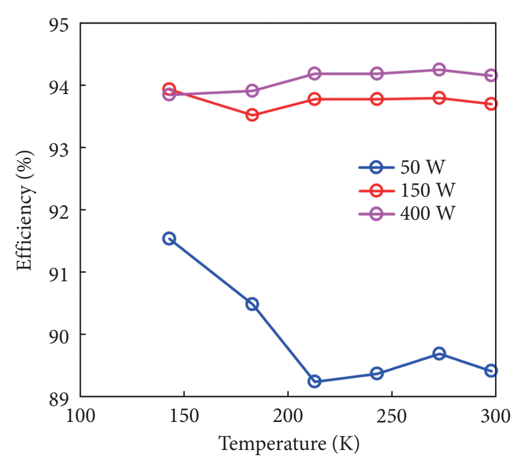

Figure 25 Efficiency performances under different conditions. Reprinted with permission from Ref [63], © 2022, IEEJ .

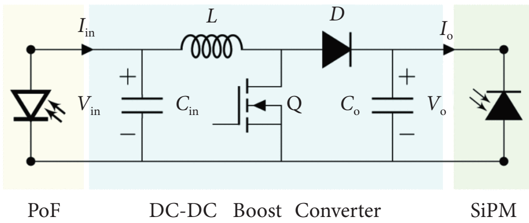

Figure 26 Schematic of the DC-DC Boost Converter. Reprinted with permission from Ref [64], © 2022, IEEE .

shown in Figure 26, NTF3055l108 Silicon MOSFETs and BAV16W diodes are chosen in this paper. The resistance of this NTF MOSFET has a resistance of about 30 mΩ at 77 K, while the resistance at 300 K is 120 mΩ. The converter was tested with two 4 V and 5 V input voltages and for various duty cycles from 10% to 90%. As shown in Figure 27, higher input voltages can have higher efficiency at most cases. When the duty cycle is lower than 50%, the efficiency for the circuits at room temperature is slightly higher than that at cryogenic temperature with a difference around 5%. The possible reason for lower efficiency at CT can be the higher switching losses at 77 K. When the duty cycle increases, the efficiency at 77 K drops even more than that at 300 K.

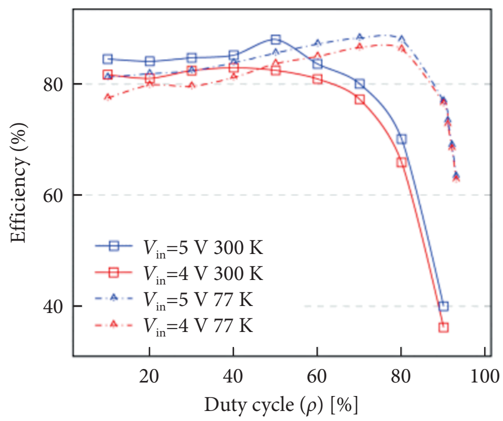

Figure 27 Efficiency at different duty cycle and temperatures. Reprinted with permission from Ref [64], © 2022, IEEE .

4 Conclusions

This article discusses the performance of semiconductor devices, passive components, gate driver, and power converters at cryogenic temperature. Some physical properties of semiconductor materials demonstrate their advantages in cryogenic temperature applications, such as higher electron mobility and saturation velocity at lower temperatures.

Diodes and MOSFETs show a 10%–80% higher forward voltage, and a slight drop in breakdown voltage with less than 30% in most cases. In these two types of devices, silicon is still a good candidate, which has 20% lower on-resistance when temperature falls to less than 100 K. However, GaN HEMTs as a rapidly developing wide bandgap devices, already have good performance at this temperature and great possibilities. Kink effect is an important defect for GaN HEMTs at low temperature, which need to be focused on and be avoided. Compared to MOSFETs, IGBTs also have higher gate-source threshold voltage with around 25% at cryogenic temperature. Because of decreased gain of the inherent PNP transistor, the fall time of IGBT decreases at cryogenic temperature.

For resistors, except for carbon composition and ceramic composition resistors, other types of resistors show a relative stable performance when temperature decreases down to 77 K. At this low temperature, capacitors also present a number of options, such as polypropylene, polyethylene, NPO ceramic, mica and polyester capacitors, with stable performance when the temperature changes. On the contrary, ceramic and electrolytic capacitors have strong temperature dependence and danger of failure. For inductors, powdered alloys present strong competitiveness at low temperature with stable permeability in low temperature.

To drive the switching devices with lower noise, some commercial gate drivers have been tested at cryogenic temperatures. However, most of them suffer under poor performance at cryogenic temperatures.

Different converters at cryogenic temperatures show some competitiveness with only slightly lower efficiency than room temperature, which affect by the changing of switching loss. However, the location near the cryogenic machine can result in a better thermal design with lower thermal leakage.

A key area of research is in the reliability of the devices and circuits. Most of the published research report results from just a handful of thermal cycles and a few hours of operation. This is not sufficient to understand the reliability and failure modes of cryogenic power electronics. Furthermore, it is often the packaging design and materials to blame for early failures, not the actual semiconductor crystal. The lack of statistics and knowledge of failure rates and failure modes could hold back further development of this otherwise promising technology.

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Additional information

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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