Selecting advanced MOSFETs for automotive power design

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From powertrains to safety systems and from comfort features to vehicle lights, MOSFETs play an important role in the modern automobile. As the electronic content of vehicles continues to grow, and as e-mobility becomes popular, these devices are becoming increasingly important. Irrespective of the target application, today's automotive MOSFETs have a vital role to play in reducing system losses - delivering better fuel economy and reduced emissions in conventional vehicles and offering longer travel distance between charges in the case of EVs and HEVs. At the same time, these MOSFETs must realize the higher power densities and better thermal performance that help designers save board space and reduce component count.

In this whitepaper we look at the evolution of DPAK and D2PAK class automotive power MOSFETs and show how the latest advances in packaging and processes are addressing today's demanding automotive applications.

Introduction

MOSFET requirements vary depending on what the device is being used for, and where it is placed in the vehicle. Manufacturers address this wide range of needs by developing broad product portfolios that offer multiple options in terms of performance and package type. These MOSFETs need to be qualified to automotive standards such as AEC-Q101.

As the demand for electronic applications grows, then the number of power devices deployed in a vehicle also rises. Voltages are increasing from 12V through 24V to 48V for the battery string. This means that the demand of 100V MOSFETs are increased.

Finally, in the increasingly dense spaces within modern vehicles, ambient temperatures are higher than in consumer, computing or even industrial applications. This brings a significant challenge to system designers as there is less margin for temperature rise in the device.

Addressing the challenges

Semiconductor companies have two main thrusts in addressing these challenges; electrical and thermal. From an electrical perspective, the semiconductor performances are constantly improved, along with the associated wafer technology to reduce resistances and capacitances in the final device. These improvements bring greater efficiencies and allow for faster switching, delivering MOSFETs suitable for today's high-power-density applications.

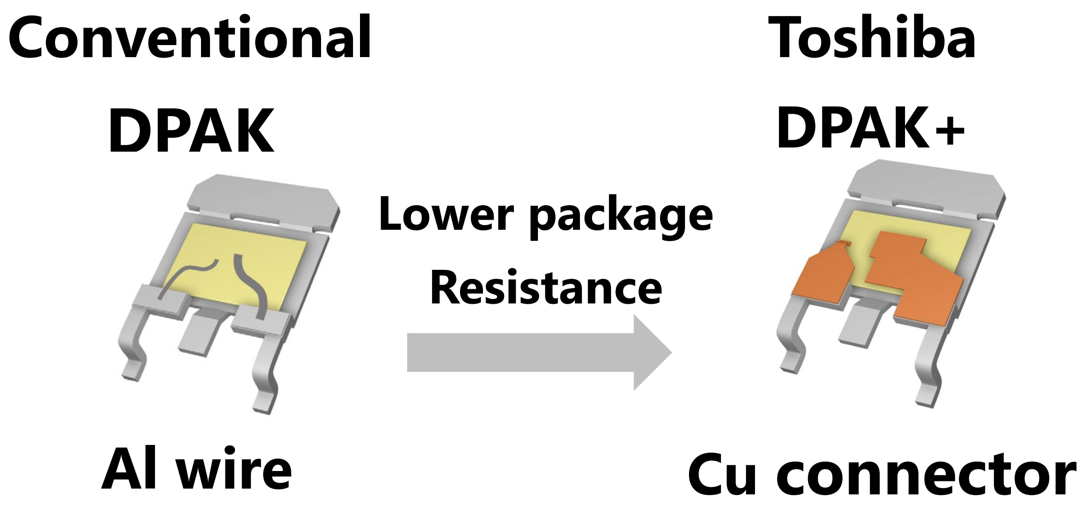
In parallel with this, development effort is being focused on the package technology. Smaller packages have to be used to realize the downsizing of ECU(Electronic Control Unit). The challenge is how to realize the same level of thermal conductivity in smaller spaces. As a result, companies are developing innovative ways to thermally connect the semiconductor junction to the outside world, enabling the greater thermal efficiencies demanded in compact high-power systems that operate at elevated ambient temperatures.

As a company that has been developing automotive power MOSFETs for many years, Toshiba is at the forefront of innovation for today's demanding vehicle applications. The company's portfolio of automotive power MOSFETs encompasses N-channel and P-channel devices (the latter are particularly useful for reverse battery protection) based on trench gate technology. Toshiba's trench processes offer the best combination of conduction and switching performance in the target voltage range.

Packaging technology advances

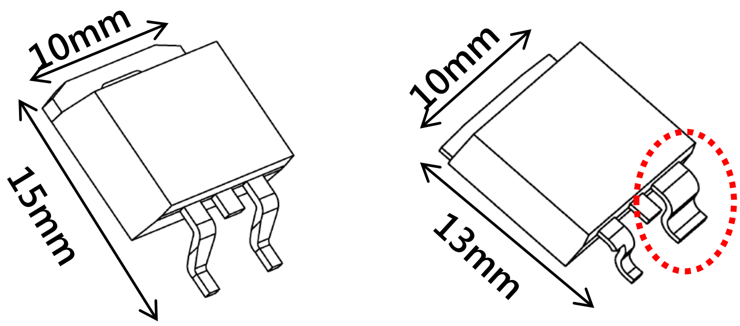
Improvements in package technology increase reliability and support higher currents for high-power automotive applications. However, the wire bonds within traditional power MOSFET packages limit current-carrying capability, and also represent a common point of failure. This is why Toshiba has developed another bonding technology.

Toshiba is unique amongst automotive power MOSFET suppliers in that the company uses copper connecters (copper clips) for internal bonding in large power packages such as DPAK and D2PAK. Other suppliers typically use conventional aluminum wire bonding. Toshiba started to use copper connecters for automotive MOSFETs in 2008 with the launch of a TO-220SM(W) package - this is Toshiba's original 10mm x 13mm SMD (Surface-Mount-Device) power package. The company has been using copper connecters for automotive DPAK (TO-252) and D2PAK (TO-263) since 2011 and 2015 respectively. DPAK+ and D2PAK+ are Toshiba's package names given to DPAK and D2PAK packages with copper connecters.



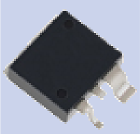
There are a number of benefits of using these copper connecters. Firstly, the contact area between source pad and source copper connecter is much larger than that between a source pad and source aluminum wires. This larger contact area leads to less planar current on the source pad metal layer. As a result, total resistance is reduced. From both a thermal and electrical conductivity perspective copper is much better than aluminum. Thermal conductivity is 401W/(m·K) for copper, while it is 237W/(m·K) for aluminum. Electrical resistivity (at 20°C) is 16.8nΩ·m for copper and 28.2nΩ·m for aluminum. Higher thermal conductivity helps release heat from the connecter element of the package and the lower resistivity contributes to the reduction of package resistance.

To maximize the benefit of its copper connecter technology, Toshiba developed the unique TO-220SM(W) mentioned previously. This 10mm x 13mm SMD power package looks similar to a D2PAK (TO-263) which has dimensions of around 10mm x 15mm. However, TO-220SM(W) has a much wider (about 3 times) and shorter source pin than a conventional D2PAKpackage.



D2PAK(TO-263) TO-220SM(W)

TO-2 2 0 SM (W) PACKAGE (10mm x 13mm)

Package	Polarity	Process	V_{DSS} (V)	Part No.	R_{DS}(ON) max (mΩ) V_{GS}=10V (-10V Pch)	R_{DS}(ON) max (mΩ) V_{GS}=6V (-6V Pch)	I_D(DC) (A)	P_D (W)	Qg typ (nC)	AEC-Q101
TO-220SM(W) Package (10mm x 13mm)										
	Nch	UMOS9	40	TKR74F04PB	0.74	0.98	250	375	227	✓
				TK1R4F04PB	1.35	1.90	160	205	103	✓
		UMOS8	40	TK200F04N1L	0.9	1.37	200	375	214	✓
			100	TK60F10N1L	6.11	9.25	60	205	60	✓
				TK160F10N1L	2.4	3.9	160	375	122	✓
	Pch	UMOS6	-40	TJ200F04M3L	1.8	2.6	-200	375	460	✓
				TJ100F04M3L	3.6	5.4	-100	250	250	✓
			-60	TJ150F06M3L	5.6	6.1	-150	300	420	✓
				TJ100F06M3L	7.1	10.7	-100	250	250	✓

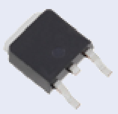
MOSFET on-resistance comparisons

Thanks to the special source pin dimensions, package resistance is reduced by about 0.15mΩ. Compare, for example, Toshiba's TK1R4F04PB 40V, 1.35mΩ (max) MOSFET in the TO-220SM(W) package with the TK1R5R04PB 40V, 1.5mΩ (max) MOSFET in D2PAK+. While both have the same chip inside, the on-resistance ($R_{DS(ON)}$) of TK1R4F04PB is 0.15mΩ lower than that of the TK1R5R04PB because of the former's wider and shorter source pin. A value of 0.15mΩ makes a substantial difference when $R_{DS(ON)}$ is in the region of few milliohms or lower. The TKR74F04PB is a 40V MOSFET in the TO-220SM(W) package with an $R_{DS(ON)}$ of just 0.74mΩ (max). This extremely low value would simply not be possible without the combination of Toshiba's established copper connecter technology, its unique TO-220SW(W) package technology, and a highly advanced wafer process.

When we talk about wafer process, $R_{DS(ON)}$ is the foremost specification for most automotive applications. 40V MOSFETs are the mainstream choice for 12V battery systems and it is worth comparing the on-resistance of 40V DPAK MOSFETs. DPAK is a standard package in the MOSFET market and users can easily compare the achievable $R_{DS(ON)}$ of different MOSFET suppliers in this standard package.

The TK1R4S04PB is Toshiba's 40V 1.35mΩ (max) automotive MOSFET in a DPAK+ package. It is the lowest $R_{DS(ON)}$ MOSFET in the automotive 40V DPAK market according to Toshiba's research as of January 2019. The second lowest value according to this research was 1.7mΩ (max) from 'supplier A' and the third lowest was 1.98mΩ (max) from 'supplier B'.

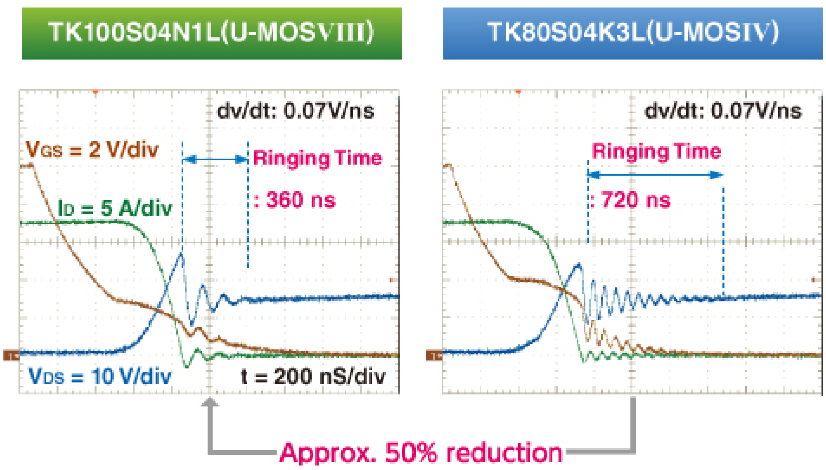
DPAK+ PACKAGE (6.5mm x 9.5mm)

Package	Polarity	Process	V_{DSS} (V)	Part No.	R_{DS}(ON) max (mΩ) V_{GS}=10V (-10V Pch)	R_{DS}(ON) max (mΩ) V_{GS}=4.5V/6V (-4.5V/-6V Pch)	I_D(DC) (A)	P_D (W)	Qg typ (nC)	AEC-Q101
	Nch	UMOS9	40	TK1R4S04PB	1.35	1.90@6V	120	180	103	✓
	Nch	UMOS8	40	TK100S04N1L	2.3	4.5@4.5V	100	157	76	✓
				TK65S04N1L	4.3	7.8@4.5V	65	107	39	✓
				TK15S04N1L	17.8	37@4.5V	15	46	10	✓
			60	TK90S06N1L	3.3	5.2@4.5V	90	157	81	✓
				TK40S06N1L	10.5	18@4.5V	40	88	26	✓
				TK25S06N1L	18.5	36.8@4.5V	25	57	15	✓
			100	TK60S10N1L	6.11	9.25@6V	60	180	60	✓
				TK55S10N1	6.5	-	55	157	49	✓
				TK33S10N1Z	9.7	-	33	125	28	✓
				TK33S10N1L	9.7	16.2@4.5V	33	125	33	✓
				TK11S10N1L	28	50@4.5V	11	65	15	✓
				TK7S10N1Z	48	-	7	50	7.1	✓
	Pch	UMOS6	-40	TJ90S04M3L	4.3	6.0@-4.5V	-90	180	172	✓
				TJ80S04M3L	5.2	7.9@-6V	-80	100	158	✓
				TJ60S04M3L	6.3	9.4@-6V	-60	90	125	✓
				TJ40S04M3L	9.1	13@-6V	-40	68	83	✓
				TJ20S04M3L	22.2	32@-6V	-20	41	37	✓
				TJ10S04M3L	44	62@-6V	-10	27	19	✓
			-60	TJ60S06M3L	11.2	14.5@-6V	-60	100	156	✓
				TJ50S06M3L	13.8	17.4@-6V	-50	90	124	✓
				TJ30S06M3L	21.8	28@-6V	-30	68	80	✓
				TJ15S06M3L	50	63@-6V	-15	41	36	✓
				TJ8S06M3L	104	130@-6V	-8	27	19	✓

Conclusion

For motors employed in a 48V battery system, the target motor power range is typically around 1~10kW. In order to drive a 5kW motor – for instance of a type employed for a BSG (Belt Starter Generator) - in such a scheme MOSFETs have to be connected in parallel to drive high current and dissipate high power. Parallel connection of MOSFETs is not something new, but it does require careful design. In particular, it is important to pay attention to the switching timing difference among paralleled MOSFETs. This is because the more difference there is in switching timing the more imbalance of switching loss there is likely to be among the paralleled devices. If one MOSFET turns on earlier or turns off later than the other MOSFETs in the parallel set-up, the switching loss concentrates around this single MOSFET. To address this issue, Toshiba released its TK160F10N1L - a new 100V, 160A power MOSFET that provides a tighter threshold voltage (V_{th}) specification than previous devices. Offering V_{th} specs of min2.5V/max3.5V versus its predecessor's min2V/max4V, the TK160F10N1L is ideal for automotive power switching applications. Thanks to this tighter V_{th} spec, switching loss is distributed more evenly among the MOSFETs.

When it comes to switching, there is another important characteristic as illustrated in the figure below. Here we see two waveforms of Toshiba MOSFETs during switch-off. The figure shows that the ringing time of the TK100S04N1L, which is based on Toshiba's UMOS8 semiconductor process, is reduced to half of that of the TK80S04K3L, which is based on an older UMOS4 process. The result is that noise emission is greatly reduced thanks to the improved dynamic characteristics of UMOS8.



Finally, it is worth noting that Toshiba has a comprehensive product portfolio of P-channel MOSFETs, which are often used for reverse battery protection or as the high-side switch of Half-/H-/B6-bridge circuits. Because no charge pump is needed to drive a P-channel MOSFET, the gate drive circuit can be very simple and cost-effective. Furthermore, the lack of a constantly switching charge pump, which gate drivers for N-channel MOSFETs usually have, can also contribute to reduced noise emissions.

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