TOSHIBA

# Induction Heating: the technology driving efficiency in home cooking appliances.

# Delivering Highly Efficient Induction Heating Cooking Appliances Using IGBTs

## Introduction

Perhaps the most impactful advert to highlight technology advancement in home appliances were those for induction hobs. A frying pan, sliced into two to leave a half-pan, lies on a sleek, dark, glass cooking hob. An egg has been broken and lies on what would have been the centre of the pan. The half on the pan has a cooked white, glistening in the light. The half on the hob remains see-through and clear, uncooked.

If nothing else, this image highlighted the fact that induction cooking would deliver energy only where it was needed, delivering it directly into the pan, making it more efficient than the gas, ceramic or spiral-wound alternatives on offer. One of the challenges is of course the more complex electronic control circuitry that it requires. While conventional heating solutions could continue to make do with simple thermostats, induction heating requires switching converters that are carefully controlled to maintain safe operation, such as the ability to detect when a pan has been placed on the hob. The electronics and semiconductor industry have responded, bringing efficient switching solutions to market that are cost optimised, enabling induction solutions to be integrated not only into cooker hobs but single cooking hobs, hot-plates, rice cookers and milk frothers. Thanks to the gas-like heat control and uniform heating achieved, induction heating is a much-liked alternative to gas cooking.

Some of the drive toward induction-based cooking comes from nationwide efforts to reduce energy consumption. Across Europe the energy efficiency labelling on home appliances has made the general public more aware of how much energy the appliances they purchase actually consume. Switching to a more energy efficient electric cooking option could save up to €230 in electricity costs over 15 years, while saving 2.7m tonnes of CO2 by 2030 across Europe[1]. Since 1990, European countries have seen a 35% reduction in household energy consumption. Although cooking is actually one of the lowest contributors to energy consumption across the European Union, in countries such as Portugal (~40%) and Romania (~28%) it is a significant contributor (figure 1).

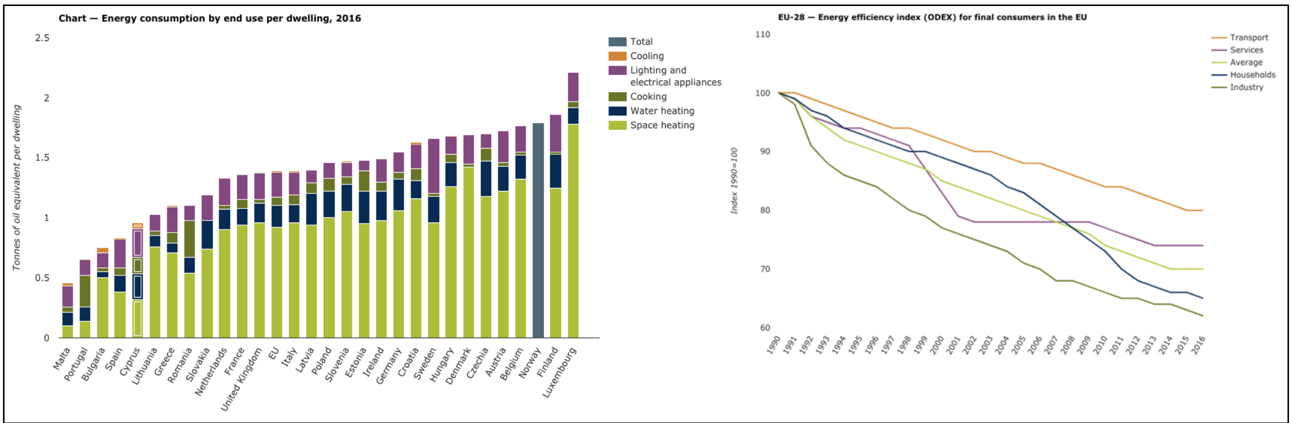


Figure 1: EU figures show cooking appliances generally have a low contribution to overall home energy consumption (left), perhaps the result of energy efficiency improvements of 35% in households since 1990 (right)[2]

# Approaches to induction heating

Induction heating follows the same basic principles as found in the common transformer. An electrical current in a coil is used to induce a current in a second coil. However, an induction hob or rice cooker uses the cooking vessel in the place of the second coil. The magnetic flux induced in the vessel cause Eddy currents to flow that, in turn, result in Joule heating due to the surface resistance of the material of which it is made. The material used for the pot has a significant impact on the Joule heating effect with magnetic materials, such as iron and magnetic stainless steel offering a higher resistance than non-magnetic materials such as aluminium and copper. In order to improve overall efficiency, the primary coil is typically made of copper and consists of many copper strands, known as a litz wire, that helps to reduce AC resistance. Due to current mostly flowing near the surface of the conductor at the high frequencies used, something known as the skin effect, a litz wire, with its many strands, effectively increases the surface area of the coil.

While there are many topologies available that make use of a half-bridge or full-bridge design, the price pressures on cooking appliances mean that many induction heating solutions utilise a soft-switching single ended parallel resonant converter (SEPR) to make a voltage-resonant circuit (figure 2). At its core is a resonant tank network consisting of a capacitor, Cr, and the litz coil, Lr. This is linked to a switch, typically an IGBT, and a parallel diode that provides the inductor's resonant current flow. These operate under zero-voltage switching (ZVS) conditions. The diode is usually integrated into the IGBT to make a single component and its forward characteristics are optimised to the needs of this type of circuit to reduce losses. The circuit is supplied from the mains via a bridge rectifier and capacitor, Cm, circuit that ensures near unity power factor. The switching frequencies used range from around 20 - 30 kHz, allowing the circuit to be used with magnetic cookware. This also places the switching frequency outside the audible range. Higher frequencies may also be used as part of a soft-start function

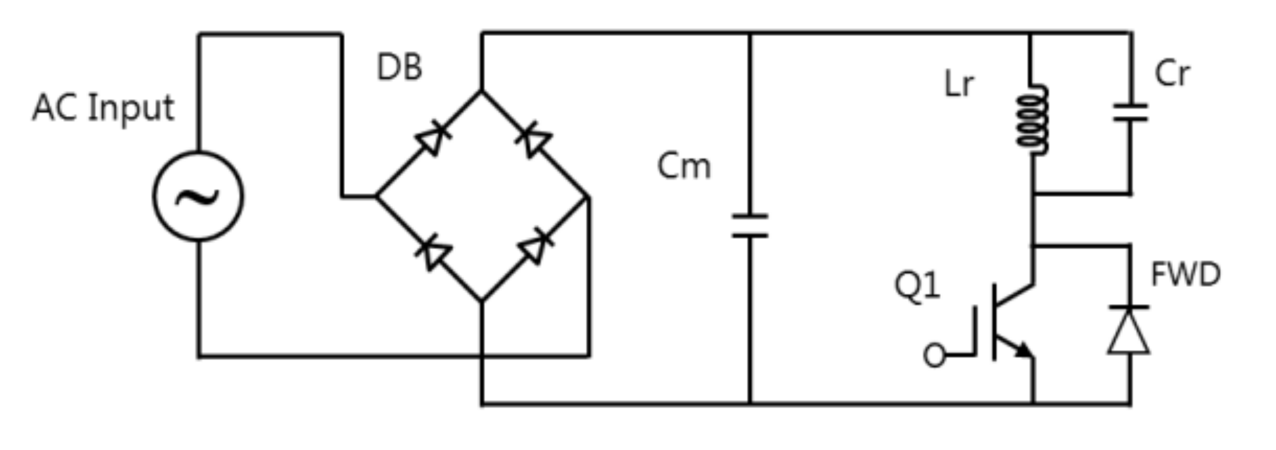


Figure 2: A single ended parallel resonance (SEPR) circuit is typically used for voltage-resonant circuits.

The operation of the voltage-resonance circuit is broken down into four time periods (figure 3) and is applicable for the case that the start-up process has been completed (i.e. Cr is full charged):

1. T1 – The cycle starts with Q1 being turned on, allowing current to flow from Cm through Lr and Q1 and causing the current flowing to increase linearly until it reaches the desired level. During this time the voltage across Cr is clamped to the voltage across Cm.

2. T2 – Next Q1 is turned off, causing Lr and Cr to go into resonance. The peak resonance voltage attained increases proportionally to the on-time T1.

3. T3 – The resonance current flow changes direction, causing the voltage over Cr to decrease.

4. T4 – The polarity of the voltage across Cr now reverses. When it exceeds the voltage across Cm, current starts to flow through the diode bringing the polarity and voltage of Cr back to that of Cm.

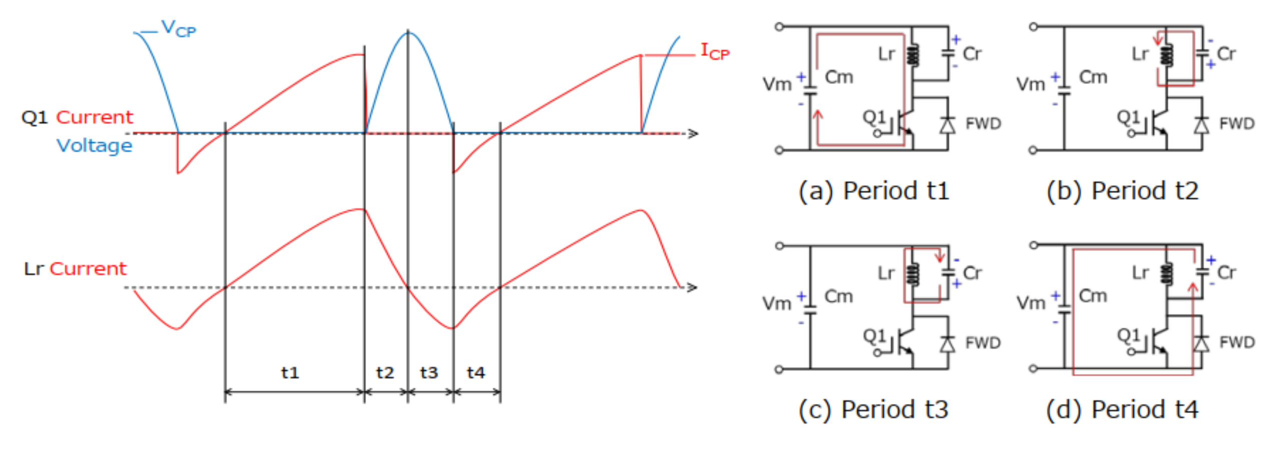


Figure 3: The four phases of operation in a SEPR voltage-resonance design.

The voltage- resonance approach results in a peak voltage across Q1 that greatly exceeds that of the peak AC supply voltage. Therefore, for 100 VAC supplies, Q1 will need its $V_{CES}$ to be rated to between 900 and 1200 V, whereas between 1350 and 1800 V is the rating required for use with 220 VAC supplies.

In the case that an application needs higher power, a half-bridge current-resonance approach can also be considered. This can also be beneficial for the implementation of all-metal induction hobs, since support for non-magnetic cookware materials requires higher switching frequencies of between 80 and 100 kHz. Compared to the voltage-resonance circuit, the current-resonance approach requires two IGBTs with parallel diodes, and the resonant circuit is a series LC or LCR construction (figure 4).

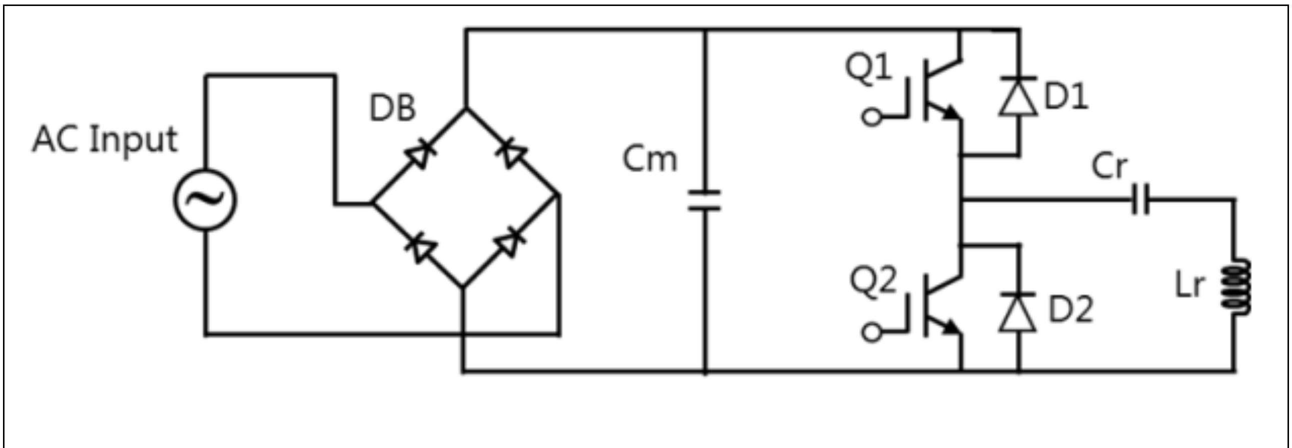


Figure 4: Induction heater half-bridge circuit with current-resonant series LC

The operation of this circuit can also be described in four phases (figure 5), once the start-up process is completed, as follows:

1. T1 – The upper switch, Q1, is turned on, resulting in a current flowing from the capacitor, Cm, into the resonance current circuit Cr-Lr.

2. T2 – Switch Q1 turns off, leaving Cr to charge due to the current flowing from Lr through the lower switch's diode.

3. T3 – Switch Q2 is turned on, allowing a resonant current to flow from Cr through Q2 and into Lr. At this point, the $V_{CE}$ of Q2 is clamped at the forward voltage of the parallel (or integrated) diode, thereby enabling a ZVS.

4. T4 – Switch Q2 is turned off, allowing a freewheeling current to flow from Lr through Cr, the diode parallel to Q1, and Cm. At this point, the $V_{CE}$ of Q1 is similarly clamped to the forward voltage of the parallel (or integrated) diode, enabling ZVS for the next phase, T1.

Due to the circuit design, the voltage appearing across the switches now does not exceed that of the sum of the peak AC input voltage. Thus, IGBTs with a $V_{CES}$ of 600 to 650 V can be used for an input of 220 VAC. Due to the higher currents involved, current-resonance is typically not used with inputs of 100 VAC.

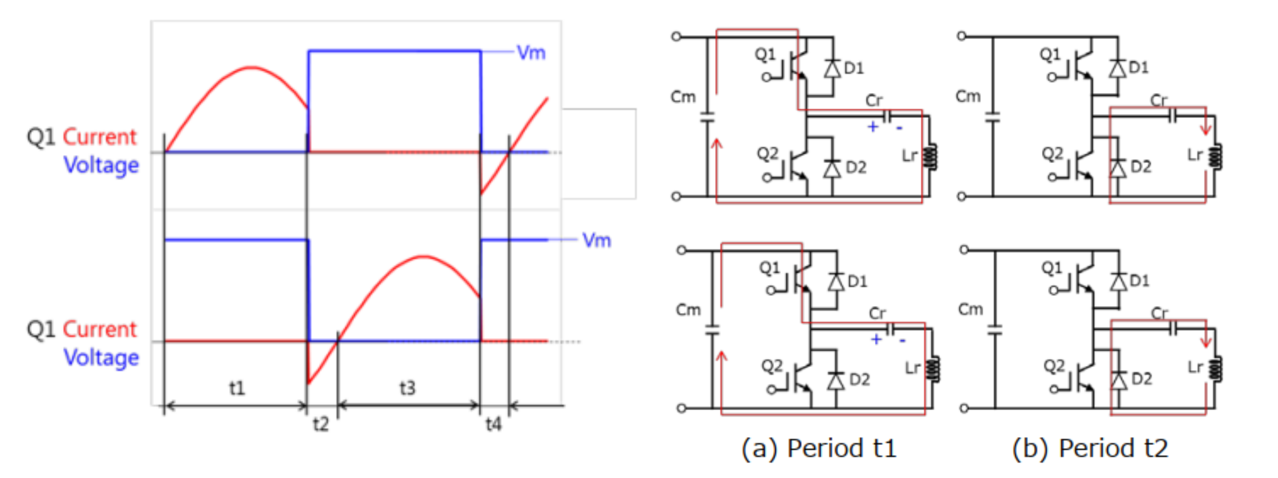


Figure 5: The four phases of operation in a half-bridge current-resonance design.

# Selecting IGBTs for induction heated appliances

Having reviewed the possible circuit approaches for induction heating applications it is possible to distil the key characteristics that need to be reviewed when selecting a potential IGBT device. Perhaps the initial consideration is to ensure the collector-emitter voltage, $V_{CES}$, provides suitable margin under all operating conditions. The large transient fluctuations in mains supply in some markets and countries (potentially up to 20%) also needs to be factored in. Also to be reviewed is the gate-emitter voltage, $V_{GES}$, which is typically driven at around 18 V to reduce power losses in the IGBT. Here it should be reviewed how much room lies between this voltage and the maximum allowed $V_{GES}$ to handle overvoltage conditions. With a consideration for total system efficiency, the forward voltage $V_F$ of the body diode should also be evaluated.

When a voltage-resonant induction heating circuit is initially switched on, the voltage across capacitor Cr is significantly less than that across Cm. At this point, a short circuit current can flow through the IGBT until the voltages are equalised. One way of handling this is to make use of the reduced current-carrying capability of the IGBT through its $I_{C(sat)}$ rating. This capability should be assessed during component selection. Additionally, the forward-biased safe operating area (FBSOA) should be reviewed that assesses the maximum permissible collector current as $I_{CE}$ increases for different pulse widths.

The next consideration is thermal performance. A lower thermal resistance $R_{th}$(j-c) will ensure that any IGBT losses result in reduced self-heating, simplifying the thermal design of the appliance. Finally, electromagnetic compatibility (EMC) should also be assessed early on in the design process. Conducted emissions typically depend mostly on the circuit board design and filter used, but radiated emissions are impacted by IGBT choice. Here the turn-off operation can make a significant difference, especially at lower testing frequencies.

## An IGBT for soft-switching induction heating applications

The technology that Toshiba has been using for its IGBTs has continuously developed, iteratively improving their performance for the needs of soft-switching applications such as inductive heating appliances. The introduction of punch-through (PT) technology, compared to non-PT types, allowed the switching speed of IGBTs to be increased at a lower total switching energy while the resulting reduced tail current proved to be better suited to soft-switching circuits. These were implemented using a thick wafer that implemented a deep P+ layer. These designs evolved to use thinner layer that achieved better forward and switching characteristics. These thin PT structure devices are known as field stop (FS) IGBTs (figure 5).

Thanks to the thin P collector layer, an N layer can be easily formed that enables the reverse conducting (RC) body diode to be implemented in the structure. These devices are known as RC-IGBTs. This body diode's characteristics depend on the location of the N layer collector electrode, its area, and other factors.

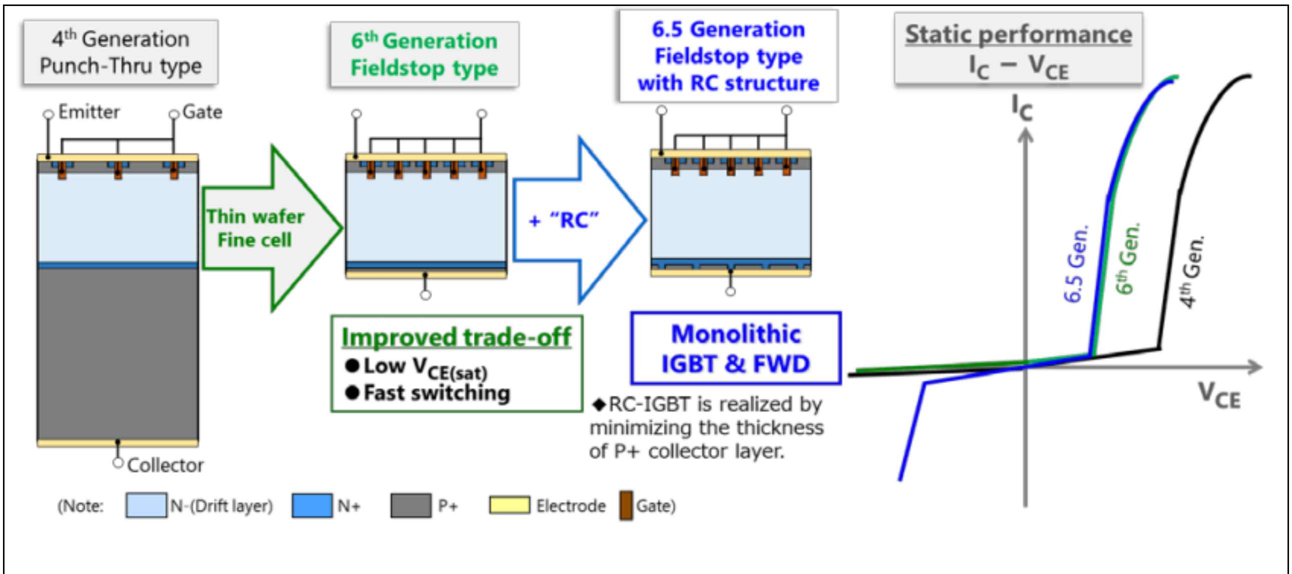


Figure 5: The evolution of Toshiba punch-through type IGBTs for soft-switching applications.

The result of this innovation is the GT20N135SRA, a 20 A and 1350 V RC-IGBT that is ideal for voltage-resonance induction heating applications targeting markets with 220 VAC supplies. This makes it suitable for medium capacity appliances handling up to 2200 W of power. Thanks to the optimisations in design highlighted, it provides many technical advantages when used in soft-switching applications.

As highlighted in the voltage-resonant circuit explanation, the turning on of the IGBT during period T1 does not cause any current to flow in it, since the voltages across the input capacitor Cm and the resonant circuit capacitor Cr are the same. However, under start-up conditions before Cr has been charged, turning on the IGBT will cause a short circuit current to flow through it. The GT20N135SRA is designed to limit this short circuit current under such conditions, with the $I_{C(sat)}$ being as low as around 150 A at 100°C. Testing during this short-circuit start-up condition shows that this IGBT, compared to previous generation devices, helps reduce the collector saturation current as well as supressing the voltage oscillation in $V_{CE}$ (figure 6).

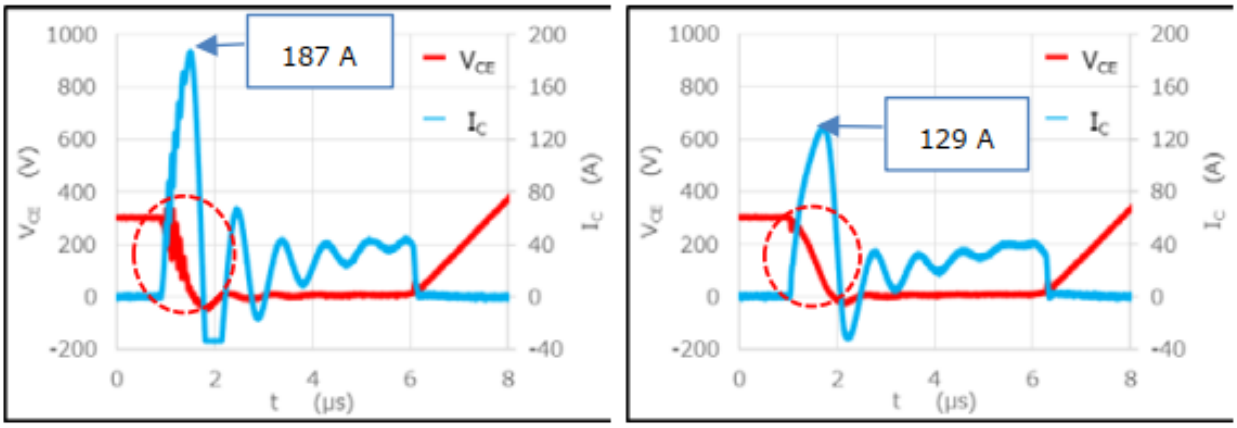


Figure 6: The short-circuit collector saturation when Cr is not charged is significantly improved in the GT20N135SRA (right) compared to the previous generation of IGBTs (left) and results in reduced oscillation (red circle)

The design of the device, both in its layout and longitudinal design, have an impact on the on maximum permissible collector current, which is described by plotting the forward-biased safe operating area (FBSOA). This operating area is significantly improved over previous generation IGBTs, as shown in figure 7, for pulse widths of 1 ms and 1 µs.

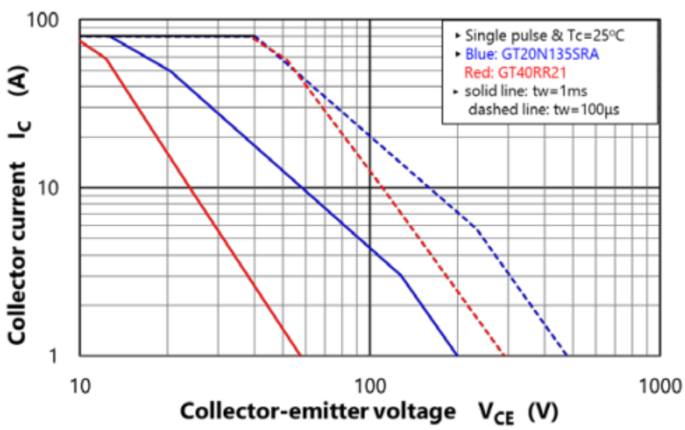


Figure 7: The GT20N135SRA offers a wider FBSOA thanks to its new layout and design

The wider FBSOA means that more current can flow in the IGBT but, due to losses, some of the energy flowing will need to be dissipated as heat. With a maximum $R_{th}$(j-c) of 0.48 °C/W, and assuming the IGBT needs to dissipate 35 W when incorporated in an induction hob appliance, this would make the difference between junction and case temperature some 6°C lower than previous IGBT products (GT40RR21 – 0.65 °C/W). This allows for more flexibility in the thermal design of the solution.

The forward characteristics of the body diode are also improved, bringing the $V_F$ down to a typical value of 1.75 V at 25°C. This is thanks to the improved N layer, which has been optimised to reduce this characteristic by around 0.5 V compared to previous generation devices, thereby reducing system losses further and increasing efficiency (figure 8).

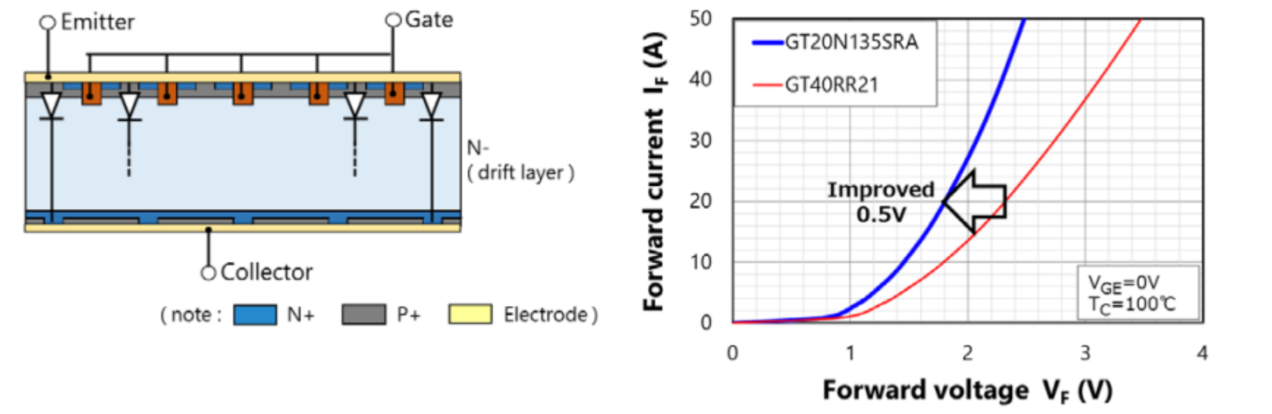


Figure 8: The body diode implementation of an RC-IGBT (left) and the improved $V_F$ offered by the GT20N135SRA (right)

EMC needs to fulfil the CISPR standard in many countries, and the turn-off operation of the IGBT plays a significant role in meeting the requirements. To meet the radiated emissions requirements, a resistor is often required in the gate path to slow the switching speed. However, this results in increased turn-off losses. The GT20N135SRA delivers a better trade-off between radiated emissions and power dissipation, delivering around 10 dB more margin at 30 MHz in the same table top induction hob appliance compared to previous IGBT devices (figure 9).

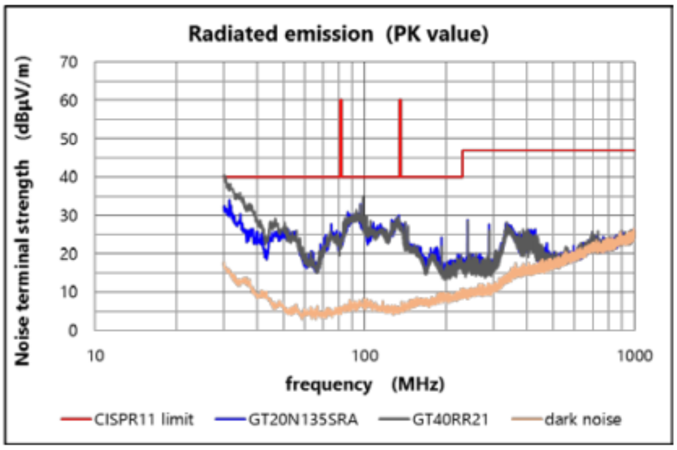


Figure 9: An improved turn-off results in 10dB more CISPR margin at 30 MHz for the same appliance

## Summary

Induction heating provides significant benefits to users, among them safety in operation by delivering heat only to the cooking vessel. However, with ever more households upgrading their cooking appliances to more efficient solutions, this technology also supports the drive to reduce CO2 emissions. The design of the electrical control systems relies heavily upon the innovations that the semiconductor can deliver through new and innovative IGBT technology. The GT20N135SRA showcases the latest design improvements that translate into higher system efficiency and safer operation, while reducing the design headaches of engineers by making it easier to fulfil radiated emissions tests and attained optimal thermal design. While the GT20N135SRA is optimised for 220 VAC voltage-resonance appliances, future products will expand the portfolio to support higher currents for higher cooking capacities and voltage-resonance solutions.



## References

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