IGBT for Voltage-Resonant Inverters: GT20N135SRA

Application Note

Outline:

Inverter systems with a resonant circuit are widely used for household cooking appliances, including IH rice cookers, tabletop IH cookers, and inverter microwave ovens. These inverter systems are roughly classified into voltage-resonant circuits in which a heating coil and a capacitor are connected in parallel and current-resonant circuits in which they are connected in series, and IGBTs are commonly used as switching devices for both applications.

In October 2019, Toshiba Electronic Devices & Storage began the production of the GT20N135SRA, a 20 A/1350 V IGBT for voltage resonance. We will continue to expand our product portfolio with IGBTs having different current and voltage ratings.

This application note discusses resonant circuits and induction heating and describes the features of the GT20N135SRA compared with those of its current product the GT40RR21.

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1. Resonant circuits

1.1. Voltage resonance

A voltage-resonant circuit is composed of a switching IGBT, a freewheeling diode (FWD), and a parallel LC circuit. It is widely used for IH rice cookers, tabletop IH cookers, inverter microwave ovens, and other applications. Figure 1.1 shows a typical voltage-resonant circuit. In this circuit, an AC input passes through a diode bridge (DB) for full-wave rectification before charging a capacitor (Cm). The charged capacitor acts as a source of voltage for a parallel LC circuit consisting of a resonance coil (Lr) and a resonance capacitor (Cr) as well as for a switching IGBT (Q1) and an FWD. Figure 1.2 shows the voltage and current waveforms applied to Q1 and the waveform of the current flowing through Lr. Figure 1.3 shows the circuit operations during periods t1, t2, t3, and t4.

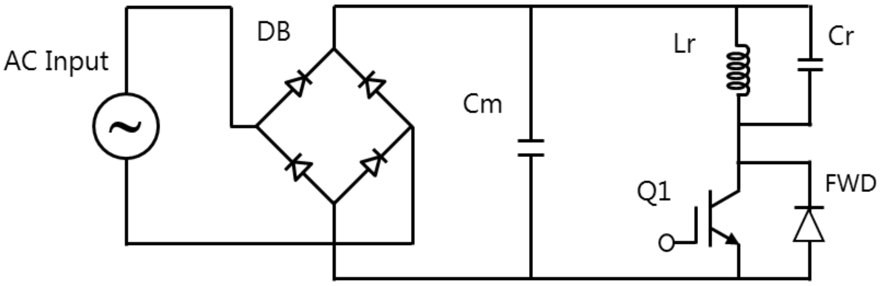


Figure 1.1 IGBT application circuit example: Voltage-resonant circuit

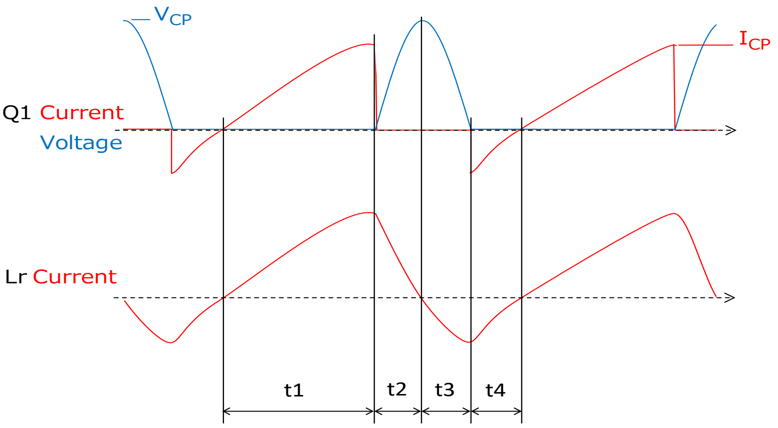
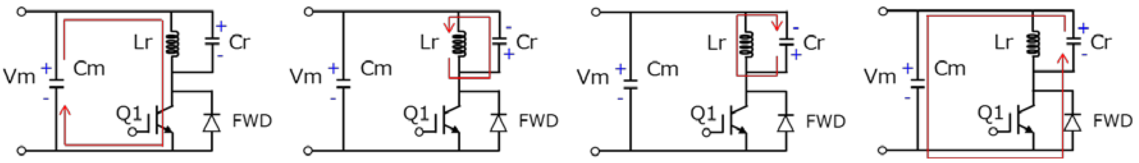


Figure 1.2 Waveforms of the voltage-resonant circuit



(a) Period t1 (b) Period t2 (c) Period t3 (d) Period t4

Figure 1.3 Operations of the voltage-resonant circuit

(a) Q1 turns on, causing current to flow through the closed loop Cm(+)－Lr－Q1－Cm(-) while increasing linearly:

$(I_{CP}=(Vm/Lr)\cdot t1)$

During period t1, the voltage across Cr (V_{Cr}) is clamped at Vm (Figure 1.3(a)).

(b) Q1 turns off, causing Lr and Cr to go into resonance. The peak resonance voltage (V_{CrP}) is calculated as:

$V_{CrP}=Vm\cdot t1/\sqrt{(Lr\cdot Cr)}$

Hence, V_{CrP} increases in proportion to t1, i.e., I_{CP}. At this time, V_{CP} (= V_{CrP}＋Vm) is applied across Q1 (Figure 1.3(b)).

(c) The direction of the resonance current generated by the LC circuit (Lr and Cr) reverses, causing the voltage across Cr to decrease (Figure 1.3(c)).

(d) The voltage polarity of Cr reverses. When the voltage across Cr exceeds Vm, current begins to flow through Cr－Cm－FWD－Cr (Figure 1.3(d)).

The above steps are repeated.

In the case of voltage resonance, the peak resonance voltage (V_{CrP}) is much higher than the peak input AC voltage. Therefore, an IGBT with a V_{CES} rating of 900 to 1200 V is used when the AC input is 100 VAC whereas an IGBT with a V_{CES} rating of 1350 to 1800 V is used when the AC input is 220 VAC.

(An IGBT with sufficient voltage rating should be selected according to a margin relative to the applied voltage.)

1.2. Current resonance

A current-resonant circuit is a series LC or LCR circuit with a half bridge consisting of two switching IGBTs. Figure 1.4 shows a typical current-resonant circuit. In household cooking appliances, the heating coil (Lr) is magnetically coupled with a load (R). Therefore, a series LCR resonant circuit is equivalently formed. Figure 1.5 shows typical voltage and current waveforms applied to each IGBT. Figure 1.6 shows the circuit operations during period’s t1, t2, t3, and t4.

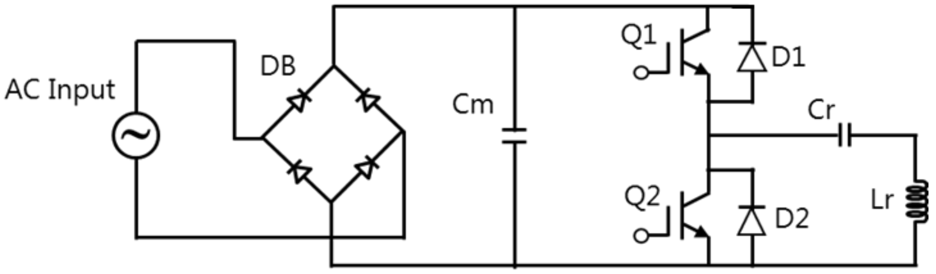


Figure 1.4 IGBT application circuit example: Current-resonant circuit

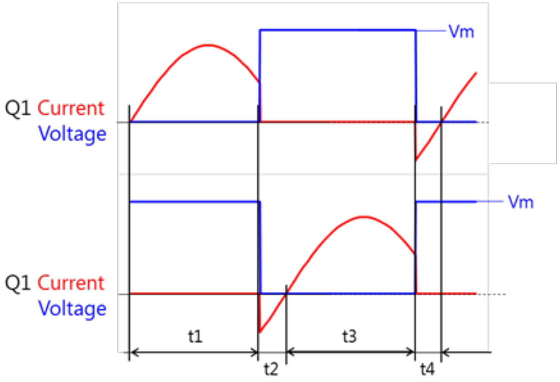
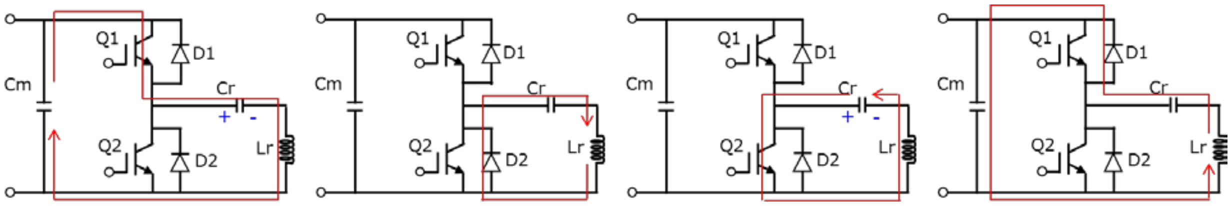


Figure 1.5 Waveforms of the current-resonant circuit



(a) Period t1 (b) Period t2 (c) Period t3 (d) Period t4

Figure 1.6 Operations of the current-resonant circuit

(a) When Q1 turns on, a resonance current (Lr･Cr) flows through the closed loop Cm(+)―Q1―Cr―Lr―Cm(-), charging Cr (Figure 1.6(a)).

(b) After Q1 turns off, Cr is charged by current flowing through Lr―D2―Cr―Lr (Figure 1.6(b)).

(c) Q2 turns on, with the collector-emitter voltage clamped at roughly -1 V (i.e., V_F of D2). This is called zero-voltage switching (ZVS). Therefore, a resonance current flows through the closed loop Cr(+)―Q2―Lr―Cr(-) (Figure 1.6(c)).

(d) When Q2 turns off, a freewheeling current flows through Lr―Cr―D1―Cm―Lr, causing the collector-emitter voltage of Q1 to be clamped at roughly -1 V (i.e., V_F of D1). This leads to the next zero-voltage switching of Q1 (Figure 1.6(d)).

The above steps are repeated.

In the case of current resonance, the voltage applied to the switching IGBTs is equal to the sum of the peak input AC voltage and the spike voltage that appears during the turn-off of the switching IGBTs. Therefore, IGBTs with a V_{CES} rating of 600 to 650 V are used when the AC input is 220 VAC.

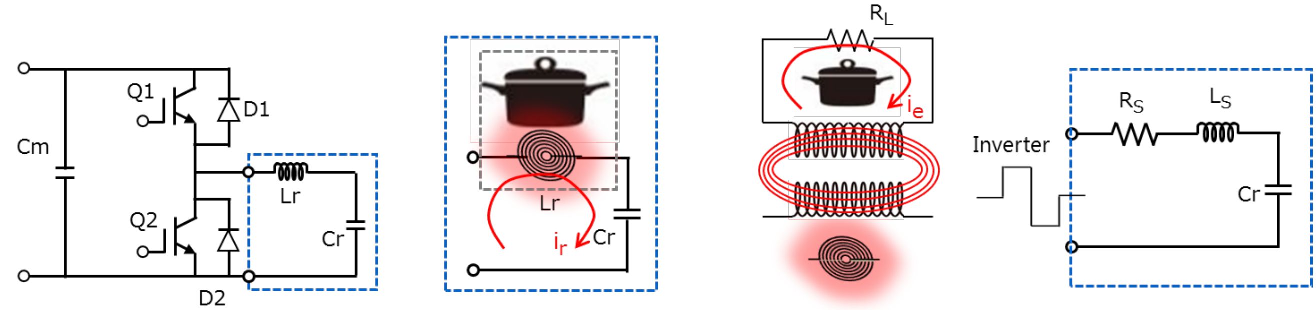
(In the case of household cooking appliances, current resonance is commonly used for applications that need to control higher electric power than voltage resonance applications or require high-frequency switching. Therefore, there are not many current resonance applications with an input of 100 VAC.)

1.3. Induction heating

IH rice cookers and tabletop IH cookers use induction heating to convert electricity into heat.

Figure 1.7 illustrates the principle of induction heating. Figure 1.7(a) shows a current-resonant circuit using an IGBT pair. Figure 1.7(b) illustrates a heating coil (Lr) and a pot heated by the current flowing through Lr. Figure 1.7(c) shows that when current flows through a heating coil, a magnetic field is formed around the coil. The alternating magnetic field generates electric currents inside the pot called eddy currents (i_e), which produce Joule heat ($i_e^2 \cdot R_L$) because of the surface resistance of the pot.

Therefore, the resonant circuit of Figure 1.7(a) can be considered equivalent to the LCR resonant circuit consisting of Ls, Cr, and Rs that operates from an output from an inverter circuit (AC) (Figure 1.7(d)). (Ls and Rs are equivalent inductance and resistance as seen from the heating coil, respectively.)



(a)Current-resonant circuit

(b)Heating coil and pot

(c)Eddy currents in a pot

(d) Equivalent circuit for resonant circuit

Figure 1.7 Principle of induction heating

The equivalent resistance (Rs) depends on the material of the pot. Magnetic substances such as iron and magnetic stainless steel have high Rs whereas non-magnetic substances such as aluminum and copper have low Rs. Rs increases as frequency increases. Therefore, when a non-magnetic pot is used as a load, it is necessary to increase frequency in order to increase Rs and thereby the amount of Joule heat generated.

In induction cooking appliances for magnetic cookware (iron and magnetic stainless steel), the resonant frequency is generally set to 20 to 30 kHz for both voltage and current resonance. Many all-metal models that also work with non-magnetic cookware (aluminum and copper) use a current-resonant circuit with a resonant frequency of 80 to 100 kHz.

2. IGBTs for soft-switching applications

Toshiba Electronic Devices & Storage has continually improved the performance of IGBTs for soft-switching applications that are used for voltage and current resonance.

The 4th and earlier generations of our IGBTs were manufactured with punch-through (PT) technology using thick wafers. The 5th and 6th generations are also PT IGBTs, but are fabricated using thin wafers to achieve better forward and switching characteristics. At present, the 6th generation is the mainstay product. (IGBTs with a thin PT structure are called field stop (FS) IGBTs.)

Since field stop IGBTs have a very thin P collector layer (called a transparent P collector layer), an N layer can easily be formed in the collector layer. Leveraging this characteristic, we have also developed reverse-conducting IGBTs (RC-IGBTs), which are now available for mass production.

Figure 2.1 shows the structures of different generations of IGBTs and their typical static characteristics.

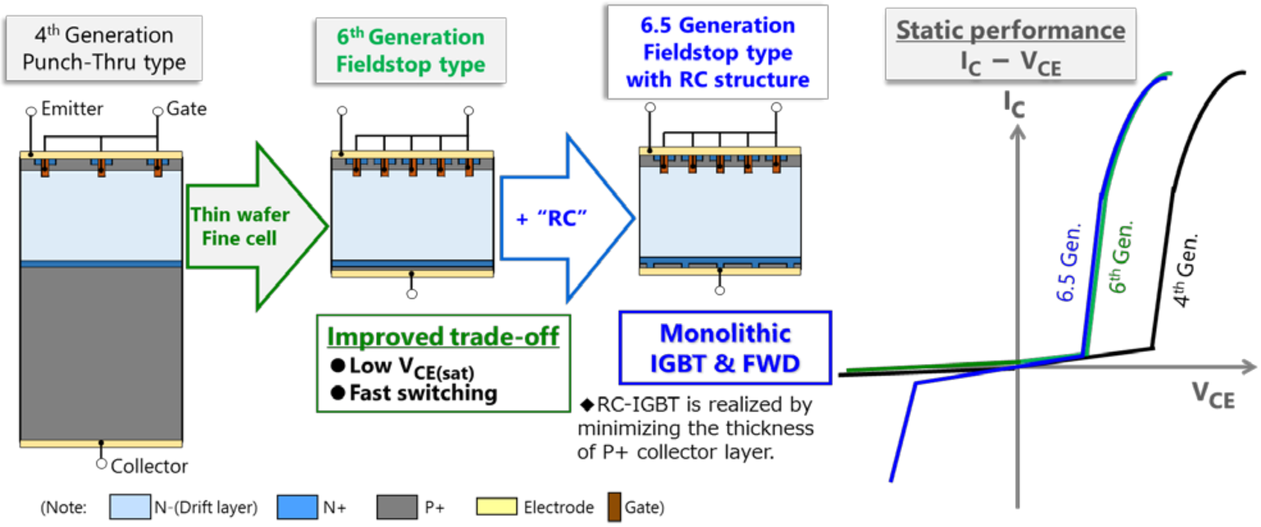


Figure 2.1 Evolution of IGBTs for soft-switching applications

The new additions to our product portfolio include 1350 V and 1100 V RC-IGBTs for voltage resonance fabricated using the newly designed 6.5 generation process that provides various features (highlighted in red in Table 2.1). In October 2019, we began the production of the GT20N135SRA, a 20 A / 1350 V RC-IGBT for medium-power applications with an input of 220 VAC. We will also develop high-current RC-IGBTs and 1100 V RC-IGBTs for voltage resonance suitable for 100 VAC applications.

Toshiba Electronic Devices & Storage is manufacturing and developing IGBTs for various soft-switching applications, as shown in Table 2.1.

Accompanying the release of the GT20N135SRA, we have modified the part naming conventions for IGBTs to make it easier to grasp their ratings, packages, and applications. Major changes are as follows:

1. Current rating: Indicates DC collector current at 100°C (Previously, the part number mainly indicated DC collector current at room temperature.)
2. Package: Indicates package type using an alphabetical letter (N: TO-247) (Previously, the part number did not contain any character that indicates a package type.)
3. Voltage rating: Indicates one-tenth of the rated voltage (135 ⇒ 1350 V) (Previously, an alphabetic notation was used.)
4. Other: Indicates applications, an internal structure, and a process generation (SRA: RC-IGBT for soft-switching applications, 6.5 generation)

Table 2.1 Lineup of discrete IGBTs for soft-switching applications

V_{CES}	IGBTs for 100 VAC voltage resonance			IGBTs for 220 VAC voltage resonance			IGBTs for current resonance
	Small Capacity (≲ 1100 W)	Medium Capacity (≲ 1250 W)	High Capacity (≲ 1400 W)	Small Capacity (≲ 1900 W)	Medium Capacity (≲ 2200 W)	High Capacity (≲ 2400 W)	
600 V							GT40J322 GT50J341 GT50JR21 GT50JR22
900 V	GT50MR21						
1000 V		GT50N322A	GT50N324				
1050 V	GT50NR21						
1100 V		GT60PR21 **S1PA6**(*)	**S1PA7**(*)				
1200 V	GT40QR21			GT40QR21			
1350 V				GT40RR21	**GT20N135SRA**	**S1PA5**(*)	
1800 V				GT40WR21			

(Black: 4th Gen., Green: 6th Gen., Blue: 6.5 Gen., Red: Under development or new)

(*: S1PA* is a prototype name being used at the development stage. It will be replaced by a formal part number when the device becomes available for mass production.)

3. Features of the GT20N135SRA, an IGBT for 220 VAC voltage resonance

The newly developed 20 A/1350 V GT20N135SRA provides various advantages over the previous equivalent device, the GT40RR21, and is easier to use for 220 VAC voltage resonance applications. (The new part naming scheme indicates the rated DC collector current at 100 °C.) The following subsections describe the advantages of the GT20N135SRA in comparison with the GT40RR21.

3.1. Reduced collector saturation current

In the voltage-resonant circuit shown in Figure 1.1, the voltages across Cm and Cr are usually equal when Q1 turns on. The turn-on current (i_C) of Q1 is expressed as i_C=(Vm/Lr)·t, which increases linearly over time (t) after turn-on. Therefore, large turn-on current does not flow to Q1. (Vm: Voltage charged across Cm)

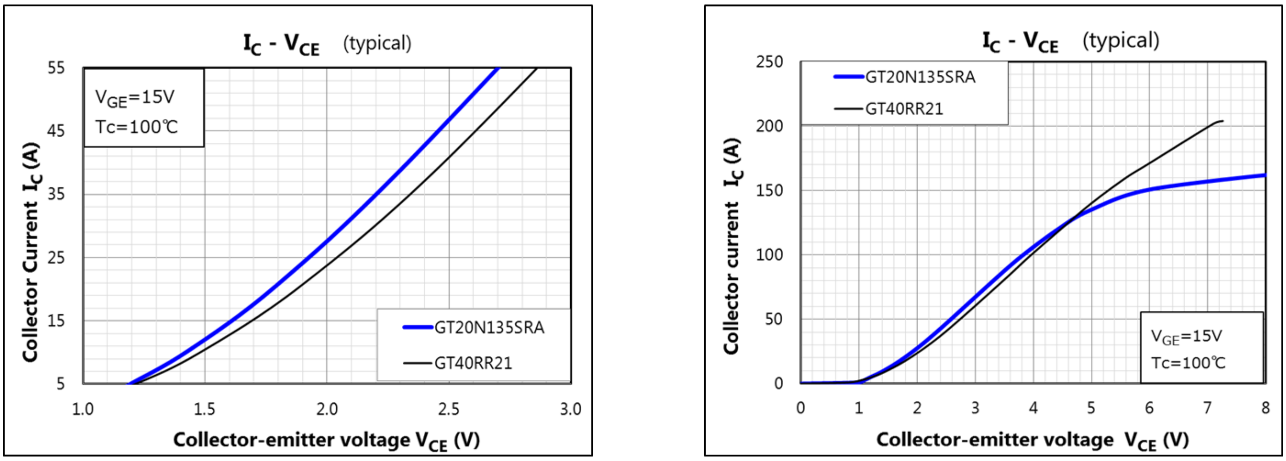
However, if Q1 turns on when the charged voltage of Cr is lower than that of Cm (e.g., at system power-on), a short-circuit current flows through Cm(+)−Cr−Q1−Cm(-). This current can be reduced in two ways: 1) using a circuit control technique called soft start and 2) reducing the current-carrying capability of the switching device used.

As shown in Figure 3.1(a), the GT20N135SRA exhibits lower collector-emitter voltage (V_{CE}) than the GT40RR21 in the current region in which they are typically used (i.e., the load current region) and therefore causes less conduction loss. In addition, the collector saturation current ($I_{C(sat)}$) of the GT20N135SRA is as low as roughly 150 A at 100°C as shown in Figure 3.1(b).

This helps reduce short-circuit current. Figure 3.2(b) and Figure 3.2(c) show the test results.

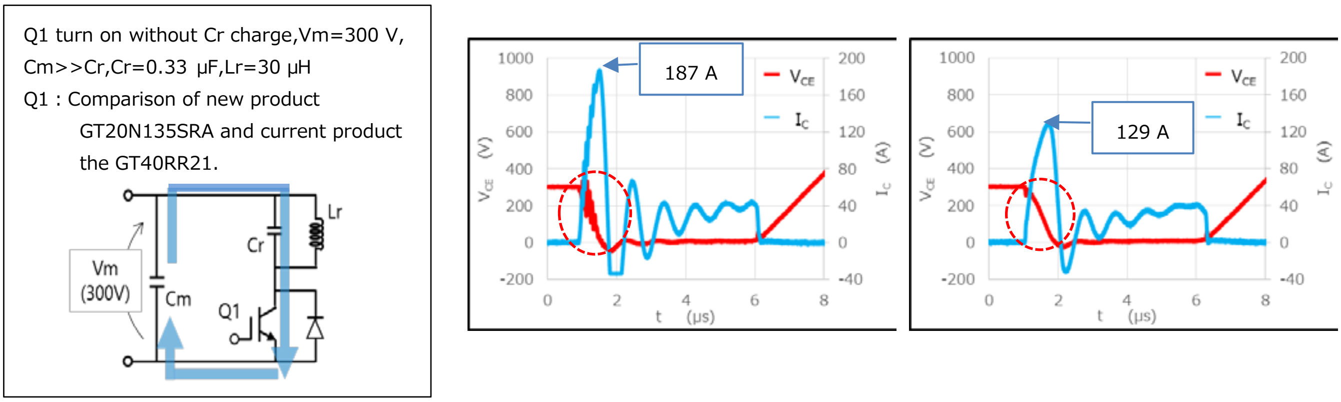
As can be seen from these figures, the GT20N135SRA helps reduce short-circuit current at power-on because of the reduced collector saturation current ($I_{C(sat)}$) (129 A as against 187 A of the GT40RR21). IGBTs are susceptible to oscillation in the short-circuit state. The GT40RR21 exhibits this tendency as highlighted by the dashed red circle in Figure 3.2(b). In contrast, the GT20N135SRA helps suppress oscillation as indicated by the dashed red circle in Figure 3.2(c).

In addition, the non-repetitive peak collector current (I_{CSM}), which provides a measure of short-circuit current at power-on, is rated at 220 A (t < 3 μs).



(a) Forward voltage drop in the load current region (b) Collector saturation current characteristics

Figure 3.1 Comparison of the forward characteristics of the GT20N135SRA and GT40RR21



(a) Test circuit

(b)Test results of the GT40RR21 (Current product)

(c)Test results of the GT20N135SRA (New product)

Figure 3.2 Test circuit for emulating inrush current and test results

3.2. Wide forward-biased safe operating area (FBSOA)

Although the GT20N135SRA and GT40RR21 have almost the same pellet size, the GT20N135SRA provides a much wider safe operating area because of the optimized pellet design (e.g., layout and longitudinal design). Figure 3.3 shows the guaranteed forward-biased safe operating areas (FBSOAs) of these IGBTs at pulse widths of 1 ms and 100 μs.

As the collector-emitter voltage (V_{CE}) increases, the difference in the maximum permissible collector current between the two devices increases. The FBSOA plots indicate that, at voltage higher than 100 V, the GT20N135SRA tolerates more than double the collector current compared with the GT40RR21.

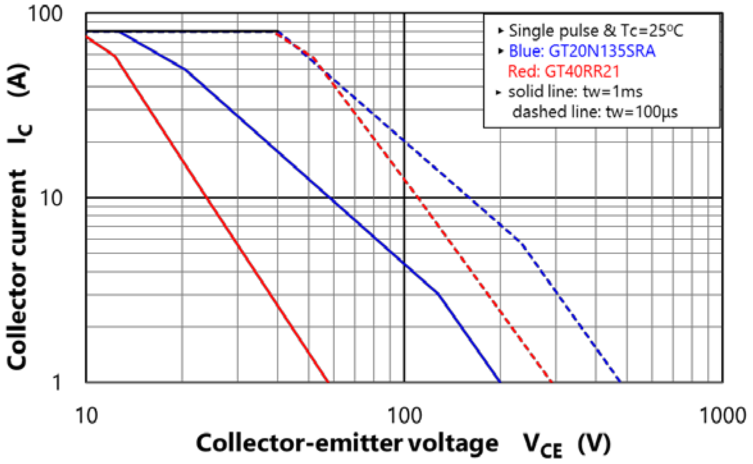


Figure 3.3 Comparison of the safe operating areas of the GT20N135SRA and GT40RR21

3.3. Reduced thermal resistance

As described above, the GT20N135SRA provides a wider FBSOA than the GT40RR21 because of the optimized pellet design. In addition, the GT20N135SRA exhibits an improvement in thermal resistance characteristics. Table 3.1 shows the junction-case thermal resistance (R_{th}(j-c)) of these IGBTs, and Figure 3.4 shows their transient junction-case thermal impedance (r_{th}(j-c)) curves.

The GT20N135SRA provides a thermal resistance 0.17 °C/W lower than the GT40RR21 and 25 to 30% lower transient thermal resistance in the time region between 0.1 and 100 ms. Therefore, the junction temperature (Tj) of the GT20N135SRA rises less than that of the GT40RR21 under the same power dissipation and heat dissipation conditions.

Suppose, for example, these IGBTs dissipate an average of 35 W when incorporated in tabletop IH cookers. Then, the difference between the junction and case temperatures (ΔTj(j-c)) for the GT20N135SRA is roughly 6 °C less than that for the GT40RR21. Therefore, the GT20N135SRA provides more flexibility in thermal design. (There will be a greater difference when a transient temperature rise at peak power is taken into consideration.)

Table 3.1 Comparison of the thermal resistance of the GT20N135SRA and GT40RR21

Part Number	Thermal Resistance, R_{th}(j-c) max
GT20N135SRA	**0.48 °C/W**
GT40RR21	**0.65 °C/W**

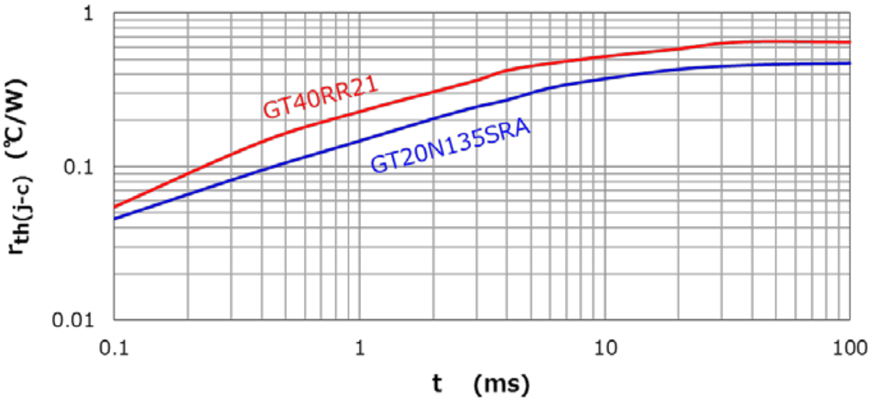


Figure 3.4 Comparison of the transient thermal resistance of the GT20N135SRA and GT40RR21

3.4. Improved forward characteristics of the body diode

Figure 3.5 illustrates the structure of the RC-IGBT used in the GT20N135SRA. In the RC-IGBT, a body diode is formed in the N layer in the transparent P collector layer. The forward characteristics of the body diode vary greatly, depending on the location of the N layer of the collector electrode, its area, and other factors.

In the GT20N135SRA, the design of the N layer is optimized to reduce the forward voltage drop (V_F) of the body diode. Therefore, the GT20N135SRA provides considerably lower V_F than the GT40RR21, as shown in Figure 3.6 (0.5 V lower at an I_F = 20 A).

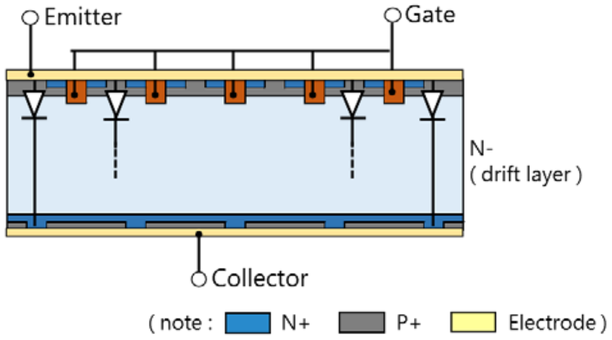


Figure 3.5 Structure of an RC-IGBT and its body diode

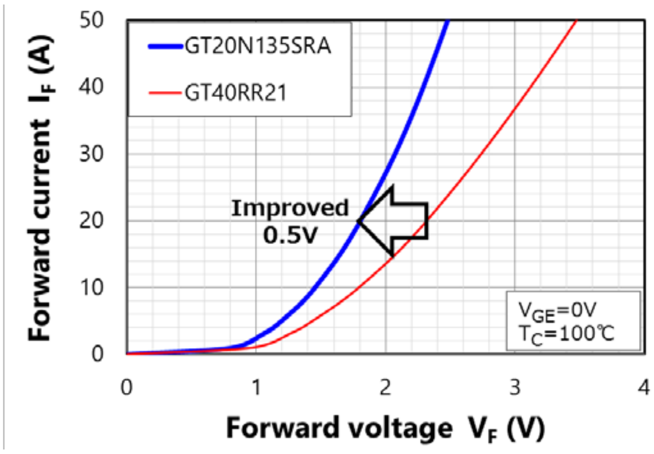


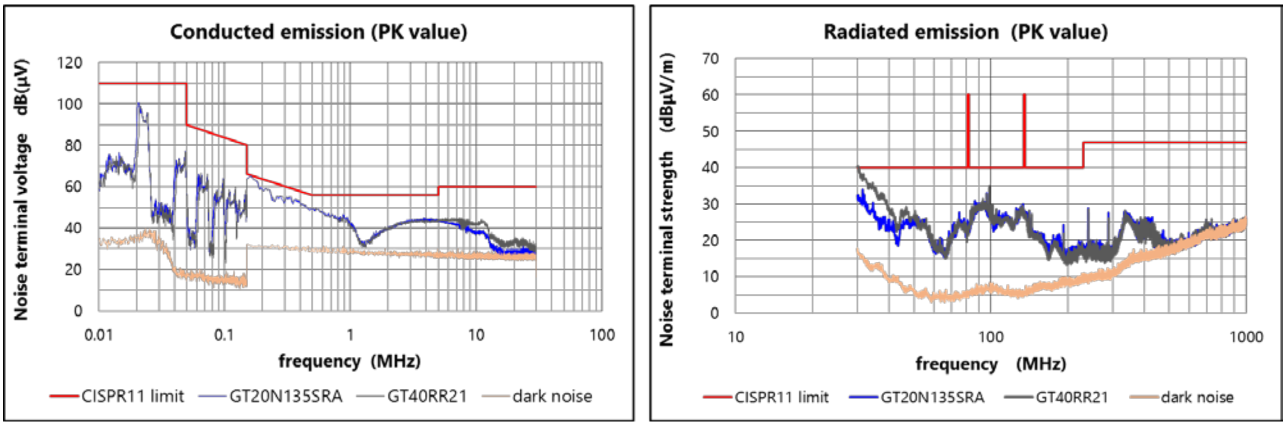
Figure 3.6 Comparison of the forward characteristics of the body diode in the GT20N135SRA and GT40RR21

3.5. Reduced radiated emissions

Electromagnetic compatibility (EMC) is regulated in many countries. The Comité International Spécial des Perturbations Radioélectriques (CISPR; English: International Special Committee on Radio Interference) provides major EMC standards. EMC depends on two factors: electromagnetic interference (EMI) and electromagnetic susceptibility (EMS). EMI is categorized into conducted emissions that travel through power supply lines and land patterns and radiated emissions that are radiated through the air as radio waves.

Figure 3.7 shows the results of measurement of conducted and radiated emissions from commercially available 220 VAC tabletop IH cookers incorporating the GT20N135SRA and GT40RR21. The magnitude of conducted emissions mainly depends on the designs of printed circuit boards (PCBs) and filters in the IH cooker and is almost unaffected by the IGBT used. In contrast, the magnitude of radiated emissions differs by roughly 10 dB at 30 MHz between the GT20N135SRA and GT40RR21. Therefore, the GT20N135SRA provides a greater margin relative to the EMI limit specified by the CISPR standard. One of the causes of this difference is a difference in the turn-off operation between the GT20N135SRA and GT40RR21. To reduce radiated emissions, a large gate resistor (RG) is generally inserted to slow the turn-off of the IGBT at the expense of an increased turn-off loss.

When compared under the same gate drive conditions, the GT20N135SRA generates less radiated emissions than the GT40RR21. Therefore, the GT20N135SRA provides a better trade-off between the power dissipation of an IGBT and a reduction in the system EMI level, reducing the burden of system design engineers.



(a) Results of conducted emission measurements (b) Results of radiated emission measurements

Figure 3.7 Comparison of the EMI noise of the GT20N135SRA and GT40RR21 (tabletop IH cooker)

4. Conclusion

Toshiba’s GT20N135SRA RC-IGBT is designed as a switching device for a voltage-resonant circuit for 220 VAC IH rice cookers, tabletop IH cookers, and inverter microwave ovens, and other cooking appliances. The GT20N135SRA provides various advantages over conventional devices, including 1) reduced short-circuit current at power-on because of the reduced collector saturation current, 2) a wider forward-biased safe operating area, 3) a reduced rise in junction temperature because of the reduced thermal resistance, 4) improved forward characteristics of the body diode, and 5) reduced radiated emissions.

Following the GT20N135SRA RC-IGBT for 220 VAC voltage resonance, we will develop high-current RC-IGBTs as well as 1100 V RC-IGBTs for 100 VAC voltage resonance.

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