Basics of Bias Resistor Built-in Transistors (BRTs)

Outline:

This document explains the operation, electrical characteristics (on-voltage, breakdown voltage of each pin, switching time, etc.) during switch operation, type, and selection method of the built-in resistor transistor (also known as BRT, digital transistor).

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1. Introduction

Semiconductor switches come in many types, including simple on-off switches and those for the selection of a signal and electrical power. This application note discusses bias resistor built-in transistors (BRTs) used as simple on-off switches as shown in Figure 1-1. Available in a single-chip implementation, a BRT is composed of a bipolar transistor and two bias resistors for switching. In Figure 1-1(b), a BRT is enclosed in a dashed box.

On-off switches should switch on and off within a specified time at a specified control voltage, have low turn-on and high turn-off resistance, and provide sufficient ruggedness. The following shows the four characteristics required for BRTs in comparison with general-purpose 60-V MOSFETs used for similar applications.

	BRT	MOSFETs
1. Voltage across switch terminals at turn-on	★★★★	★★
2. Withstand voltage across switch terminals at turn-off	★★★	★★★
3. Control voltage	★★★★	★★
4. Switching time	★★	★★★

The greater the number of ★, the better.

a) Switching circuit

b) Switching circuit using a BRT
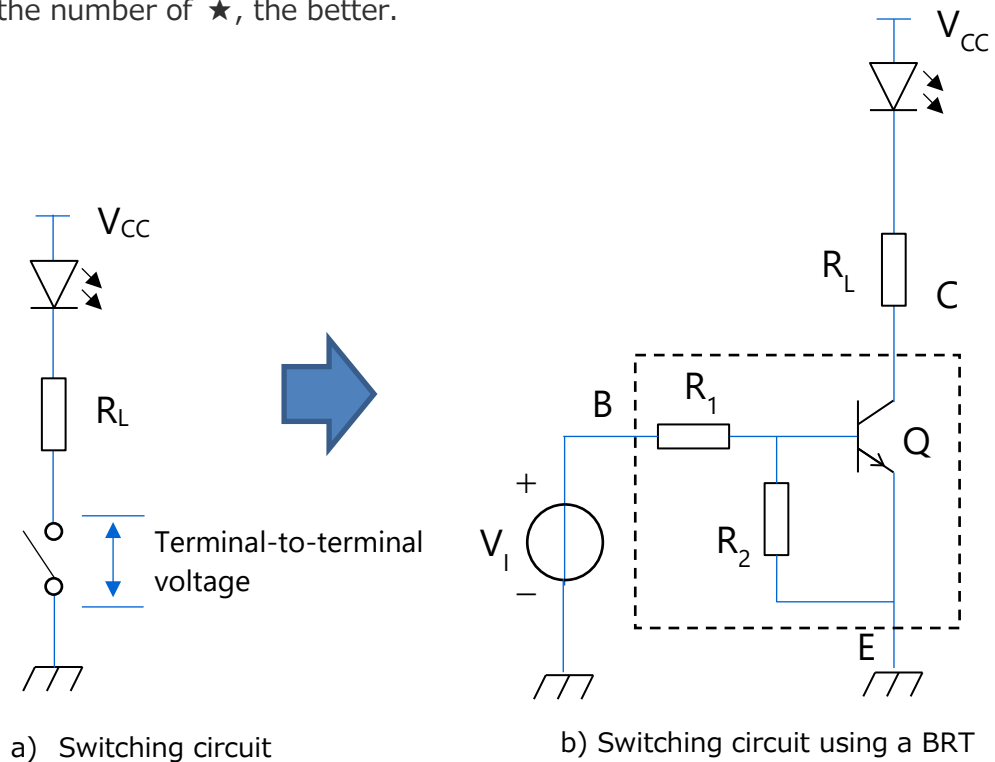
Figure 1-1 Switching circuit

The advantages of MOSFETs also include ease of device selection (i.e., ease of circuit design) and zero reactive current (i.e., power-saving). However, BRTs can also be used to configure switches at low cost if you understand selection guidelines for BRTs.

In the case of an NPN BRT like the one shown in Figure 1-1(b), R_1 converts the control voltage applied to the base (B) terminal into current in order to stabilize the switching operation. In the off

state, the control signal preceding the BRT might assume the high-impedance state. In that case, R_2 acts as a pull-down resistor, pulling the base voltage to the GND level.

Without R_2, the leakage current or the collector cut-off current (I_{CBO}) flowing from the input at turn-off might cause the BRT to malfunction because of the charge accumulated in the base region. R_2 helps prevent malfunction by passing leakage current to GND.

In the case of a PNP BRT, R_2 acts as a pull-up resistor. There is no difference in the effects of R_1 and R_2 between NPN and PNP BRTs.

The bipolar transistor in the BRT has three distinct regions of operation: saturation, active, and cut-off regions. In the active region, the collector current is basically the base current times a given current gain. It is a current-driven device since the collector current is controlled via the base current. The ratio of the collector current to the base current in the active region (called the DC current gain) is represented by h_{FE}, which is 70 to 700 in the case of general-purpose bipolar transistors. As the base current is increased along the load line as shown by the arrow in Figure 1-2, the collector current increases proportionally according to h_{FE}. When the base current is further increased, h_{FE} decreases as the gaps between collector-emitter voltage curves become narrower. If the base current is increased further on the load line, the collector current will no longer increase. This region is called the saturation region. The BRT, which is used as a switch, is operated in the saturation region as well as in the cut-off region in which the bipolar transistor is off.
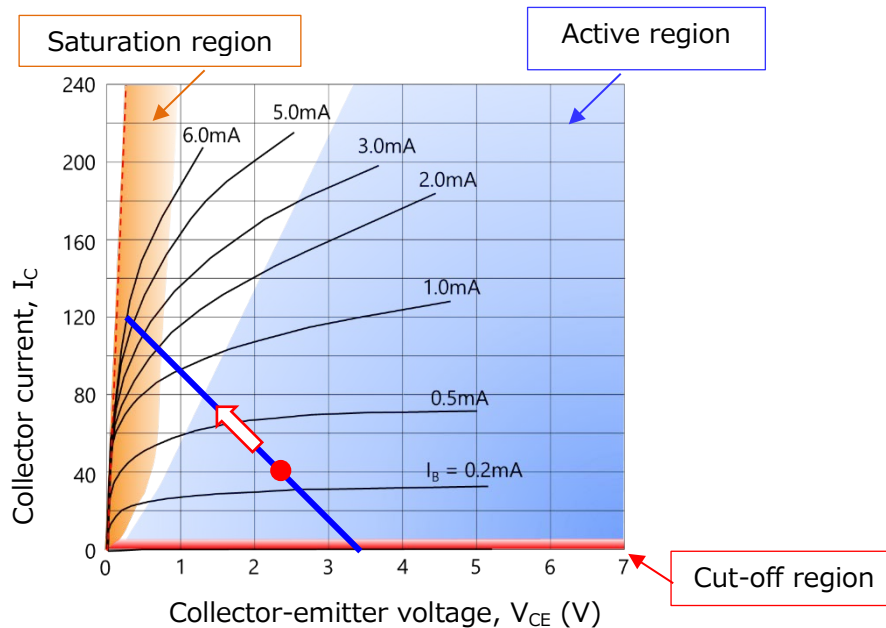

Figure 1-2 Static characteristics of the BRT (I_C − V_{CE} curves)

2. Operation of the BRT

This section describes how a BRT incorporating an NPN bipolar transistor turns on in the saturation region when the control voltage (V_I) applied to the B terminal is increased from the off state. For the sake of simplicity, let's consider the operation of a simple circuit shown in Figure 2-1.

1. The bipolar transistor, Q, is off.

   V_I is gradually increased. Since Q is initially off, the current due to V_I flows only to R_1 and R_2. Therefore, V_I is divided by R_1 and R_2, and V_b is applied to the base (b) of Q.

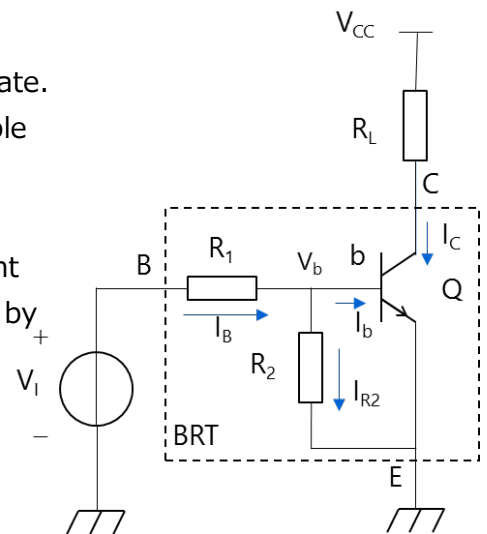 $V_b = \{R_2 / (R_1 + R_2)\} \times V_I$

Figure 2-1 Circuit used for the explanation of BRT operation

2. Q turns from off to on.

   When V_b reaches roughly 0.6 V, the base current (I_b) begins to flow, turning on Q, as indicated by the $V_{BE(sat)}$ - I_C curve shown in Figure 2-2. This causes the collector current, which is I_b times h_{FE}, to flow. At this point in time, Q is still in the active region, not in the saturation region. Therefore, its h_{FE} is 120 to 700, as is the case with the h_{FE} of general-purpose bipolar transistors (such as the 2SC2712).

3. Q is on. (Transition from the active region to the saturation region)

   As V_I increases further, V_{BE} increases. When the base voltage (V_b) of the internal bipolar transistor is higher than 0.6 V, a slight increase in V_b causes an exponential increase in the collector current (I_C) as shown in the $V_{BE(sat)}$ - I_C curves of Figure 2-2.

   Therefore, once Q turns on, V_b remains almost constant without being affected by the division of V_I by R_1 and R_2. All the excessive current (I_B - I_{R2}) flowing through R_1 flows as the base current (I_b) to the bipolar transistor. When the bipolar transistor turns on, it is still in the active region where the collector current (I_C) is $I_B * h_{FE}$. However, since the collector-emitter voltage (V_{CE}) is equal to $V_{CC} - R_L * I_C$, V_{CE} decreases suddenly because of an increase in I_C, causing the bipolar transistor to enter the saturation region.

   In this region, both the base-emitter and base-collector pn junctions are forward-biased. Therefore, a large number of minority carriers are accumulated in the base region.

4. Q turns from on to off.

   The voltage on VI is reduced. However, reducing V_I below the voltage specified as "input voltage (OFF)" does not cause the bipolar transistor to turn off immediately. This is because the collector current continues flowing until all the minority carriers in the base region are discharged through R_2 or disappear as a result of recombination with majority carriers. The time required for this operation is called the storage time, t_{stg}. Q turns off after the minority carriers disappear.
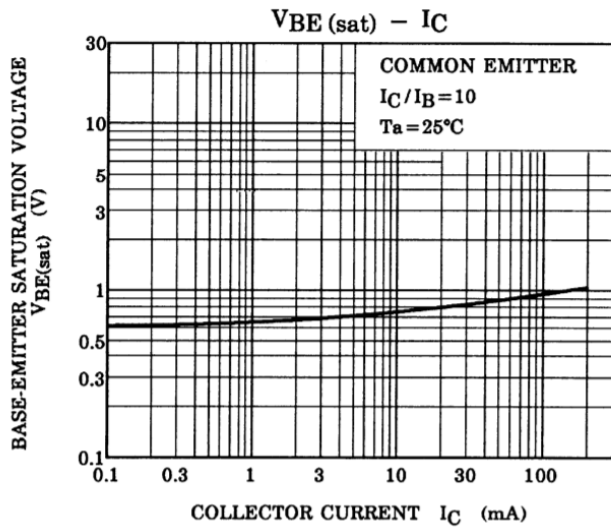
Figure 2-2 $V_{BE(sat)} - I_C$ curves (2SC2712)
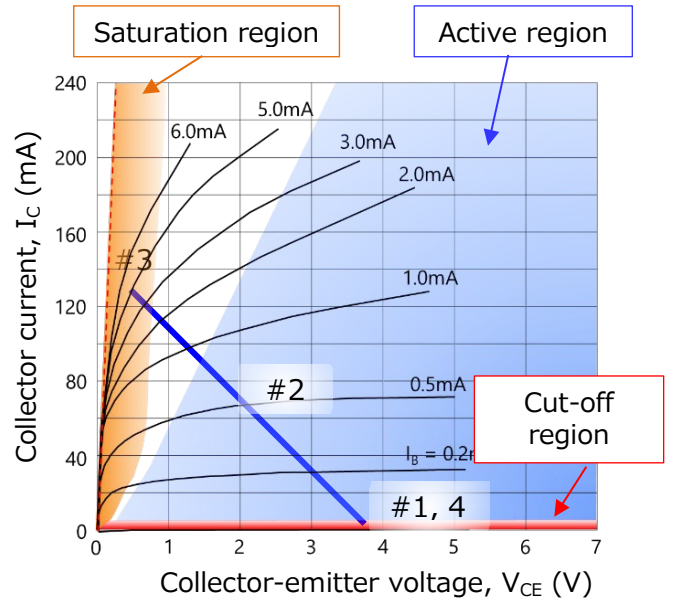
Figure 2-3 Operating locus of the BRT

3. Electrical characteristics as a switch

The electrical characteristics of a BRT depend on the values of the internal resistors used. As mentioned in the comparison between BRTs and 60-V MOSFETs in Section 1, it is necessary to select the optimum BRTs. This section describes major electrical characteristics of BRTs and basic guidelines for BRT selection.

3.1. Voltage across switch terminals at turn-on ($V_{CE(sat)}$)

$V_{CE(sat)}$ is the collector-emitter voltage (V_{CE}) when the BRT turns on.

It is desirable to select BRTs with low $V_{CE(sat)}$.

a) Mechanical switch

b) BRT switch

Figure 3-1 Voltage across switch terminals

The resistance between the terminals of a mechanical switch becomes almost zero when it is closed. However, for a BRT, it is necessary to use it in the saturation region where the collector-emitter resistance is low (i.e., the collector-emitter voltage is low). In the active region, the collector current increases proportionally with the base current according to h_{FE}. In contrast, in the saturation region, h_{FE} decreases as the saturation level increases (i.e., V_{CE} decreases). Figure 3-2 shows the I_C–V_{CE} curves of a BRT, in which a load line at a V_{CC} of 5 V is highlighted in red. The load line intersects the I_B = 0.2 mA curve at a V_{CE} of 3.8 V, which means h_{FE} = 160 when I_B = 0.2 mA. However, the load line i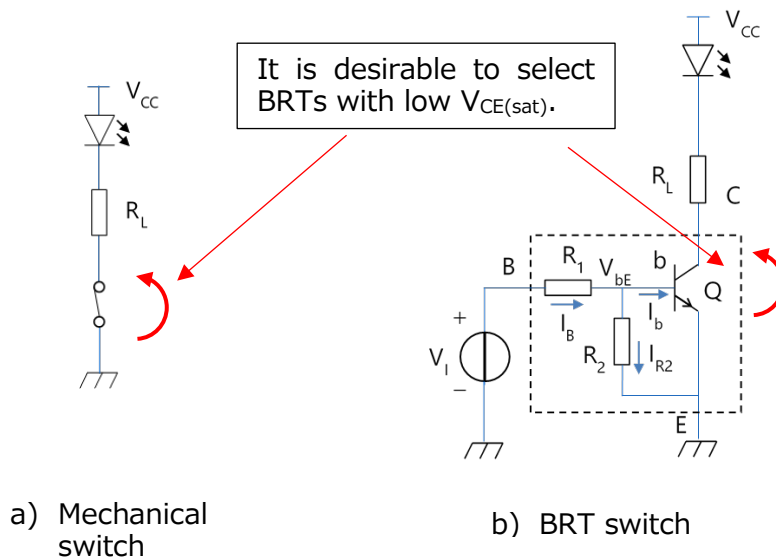ntersects the I_B = 6 mA curve at a V_{CE} of 0.2 V, meaning h_{FE} = 20. Therefore, there are two ways to reduce the collector-emitter voltage (V_{CE}):

1. Reducing the collector current (Increasing the load resistance, R_L).
   (Red load line ⇒ blue load line)
2. Increasing the base current I_b.
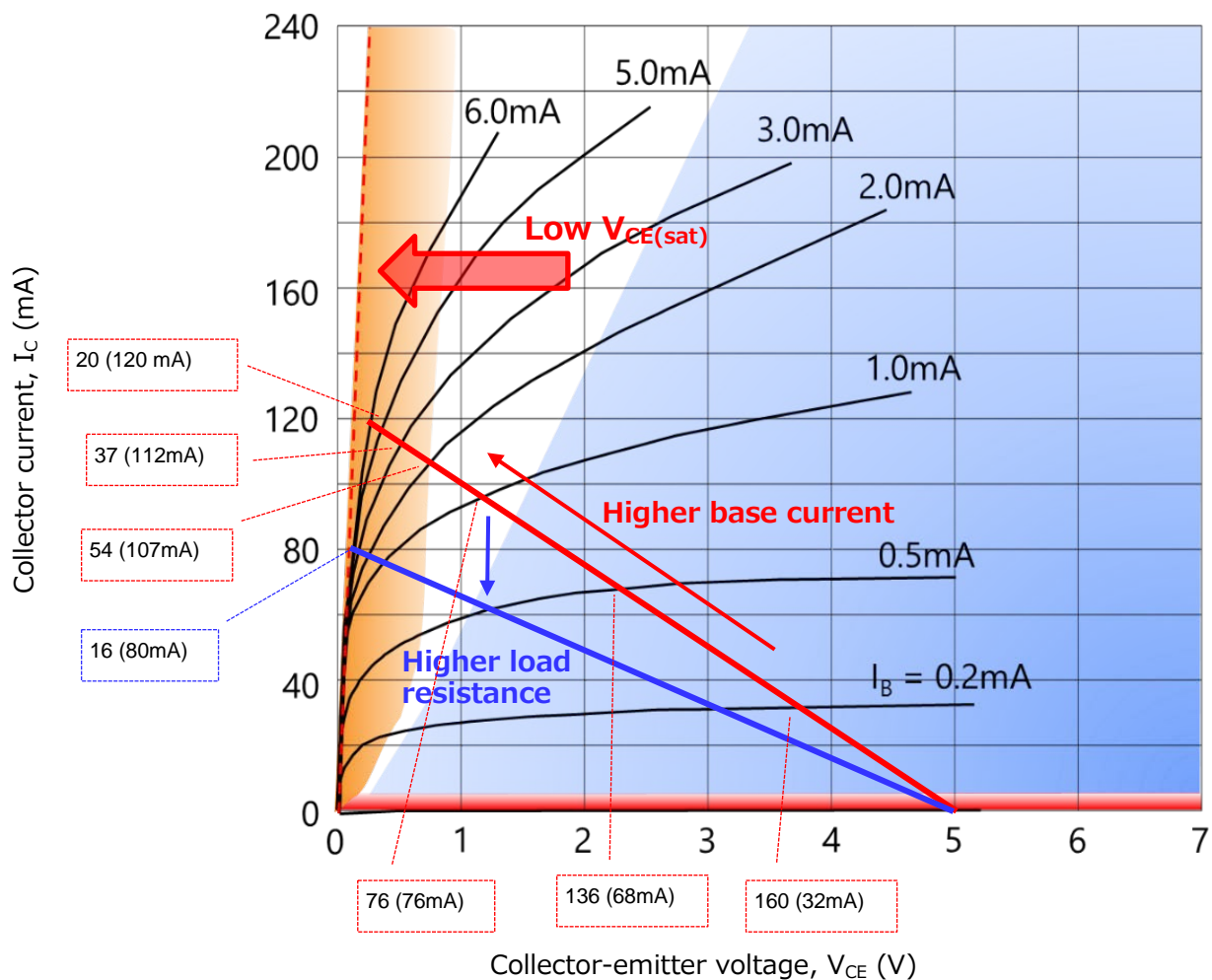
Figure 3-2 Reducing the collector-emitter saturation voltage, $V_{CE(sat)}$

Since the first way of reducing $V_{CE(sat)}$ by increasing R_L affects the load current (I_C), the collector current can only be reduced to the extent permitted by the design requirements. Here, let's see how increasing the base current helps reduce $V_{CE(sat)}$. Look at the circuit shown in Figure 3-1(b). The assumption is that we are changing the control voltage (V_I) for the RN1102 BRT (with R_1=R_2=10 kΩ) from 0 V to 5 V.

Without the bipolar transistor, increasing V_I from 0 V to 5 V would obviously cause the voltage at b (V_b) to change from 0 V to 2.5 V because of the ratio of the R_1 and R_2 values. In reality, however, V_{bE} increases only up to roughly 1 V as shown in Figure 3-3 because of the presence of the bipolar transistor. The remaining current flows to the base terminal as I_b:

$$I_b \ = \ I_B - I_{R2} = (\ V_I - V_{bE} \ ) \ / \ R_1 - V_{bE} \ / \ R_2$$

As indicated by this equation, I_b can be increased by increasing I_B and reducing I_{R2} using a BRT with:

- Small R_1 value
- Large R_2 value

What is important here are the absolute values of R_1 and R_2, not the ratio of R_1 to R_2.

The collector-emitter saturation voltage increases as temperature increases, as shown in Figure 3-4. Take the above characteristics into consideration to achieve the optimum design.
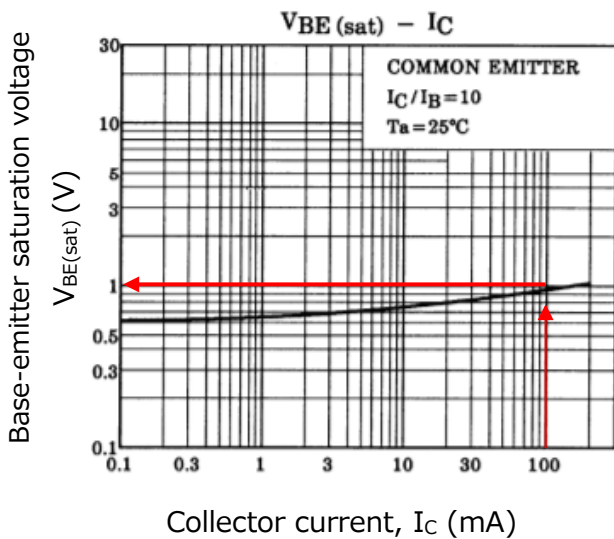
Figure 3-3 $V_{BE(sat)}$ – I_C curves (2SC2712)
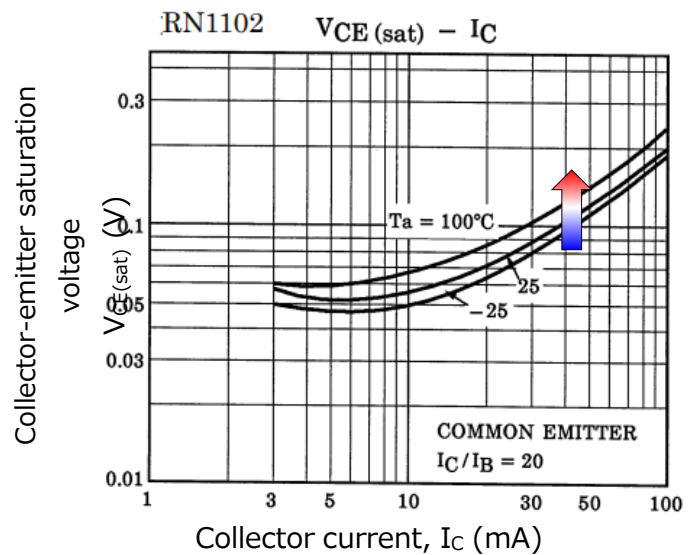
Figure 3-4 $V_{CE(sat)}$ – I_C I_C curves (RN1102)

3.2. Withstand voltages

The withstand voltages that should be considered are the maximum voltage applied across the switch terminals at switch-off as well as the maximum and minimum control voltages.

3.2.1. Maximum voltage across switch terminals at switch-off (collector-emitter withstand voltage)

This is defined as the collector-emitter voltage (V_{CEO}) with the base (B) open. Toshiba's BRTs incorporate a general-purpose bipolar transistor similar to the 2SC2712 and 2SA1162 with a collector-emitter voltage of 50 V.

3.2.2. Control voltage (maximum and minimum emitter-base voltages, V_{EBO})

Forward direction:

As the control voltage increases, the BRT transitions from the off state to the on state.

In the case of a general bipolar transistor without resistance, as the control voltage is increased after turn-on, its collector current or collector power dissipation reaches the maximum rated value if it is in the active region, making it impossible to increase the control voltage any further. If the bipolar transistor is in the saturation region, its operation is often constrained by the rated base or collector current.

Since BRTs are usually operated in the saturation region, care should be exercised as to the base and collector currents. The allowable power dissipation of the bias resistors of a BRT is specified as 1/8 W. Accordingly, the maximum control voltage (V_I) is basically determined as described below:

1. When R_1 is large: Power dissipation of R_1
2. When R_1 is small: Maximum collector current (I_C)

1. Power dissipation of R_1

   Let the base-emitter voltage of the internal bipolar transistor at turn-on be V_{be}.

   Then, the current flowing through R_1 (I_B) is expressed as follows.

   For the sake of simplicity, the assumption is $V_{be} = 0.7$ V.

Figure 3-5 Forward control voltage

$$I_B = (V_I - V_{be}) / R_1 = (V_I - 0.7) / R_1$$

The power dissipation of R_1 due to I_B must not exceed 1/8 W. Hence:

$$1/8 \text{ W} > R_1 * \{(V_I - 0.7) / R_1\}^2$$
$$> (V_I - 0.7)^2 / R_1$$
$$V_I < (R_1 / 8)^{1/2} + 0.7 \qquad\qquad (1)$$

2. Maximum collector current (I_C)

   The current flowing to the base (b) of the internal bipolar transistor (I_b) can be calculated by subtracting the current flowing to R_2 (I_{R2}) from I_B:

   $$I_b = I_B - I_{R2} = (V_I - V_{be}) / R_1 - V_{be} / R_2 = (V_I - 0.7) / R_1 - 0.7 / R_2$$

   Since the collector current (I_C) is equal to I_b times h_{FE} under operating conditions, the following equation must be satisfied:

   $$I_C(max) > I_C = h_{FE} * I_b = h_{FE} * \{(V_I - 0.7) / R_1 - 0.7 / R_2\}$$
   $$V_I < R_1 * I_C(max) / h_{FE} + (R_1 + R_2) * 0.7 / R_2 \qquad\qquad (2)$$

The lower of the V_I values calculated based on the following two factors is the maximum allowable V_I value.

Figure 3-6 indicates the tendency of the maximum V_I value, although it should be considered merely as a guide. Basically, V_I is determined by the allowable power dissipation of bias resistor R_1 (1/8 W). However, the maximum V_I value depends on the rated collector current (I_C) when R_1 is small and h_{FE} is relatively large.
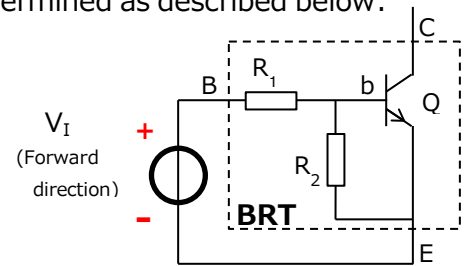
The maximum input voltage (V_I) depends on h_{FE}.

I_C - V_I @h_{FE}=10
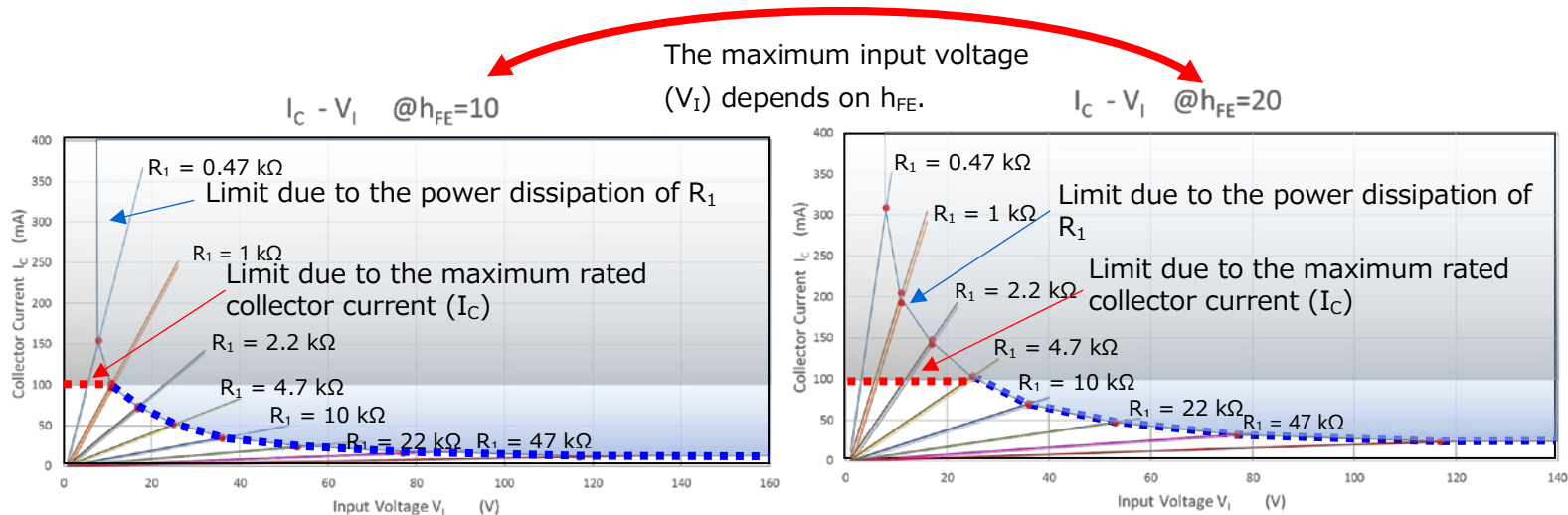
I_C - V_I @h_{FE}=20

Figure 3-6 Collector current (I_C) vs. input voltage (V_I) (left: h_{FE}=10, right: h_{FE}=20)

Reverse direction:

Let's consider the emitter-base voltage of the internal bipolar transistor (which is equivalent to the general-purpose bipolar transistors of the 2SC2712/2SA1162 class). The emitter is the positive side of the transistor. In the case of bipolar transistors without bias resistors, the emitter-base voltage is represented by V_{EBO}. In the case of BRTs, the internal bipolar transistor is off when the emitter-base voltage is applied. Therefore, the emitter-base voltage is determined by $R_2 / (R_1+R_2)$. And therefore, BRTs with a higher resistor ratio (R_1/R_2) provide higher V_{EBO} as shown in Figure 3-6.

The reverse voltage is the overshoot / undershoot (negative voltage) that occurs when the control input voltage VI reverses, and the voltage at the emitter terminal may become higher than the voltage at the base terminal. Care should be exercised to prevent such a situation.
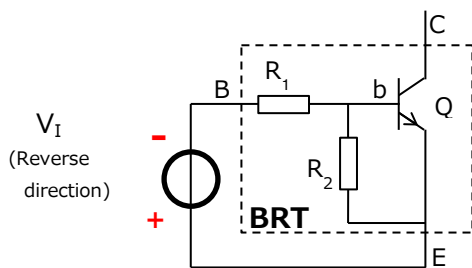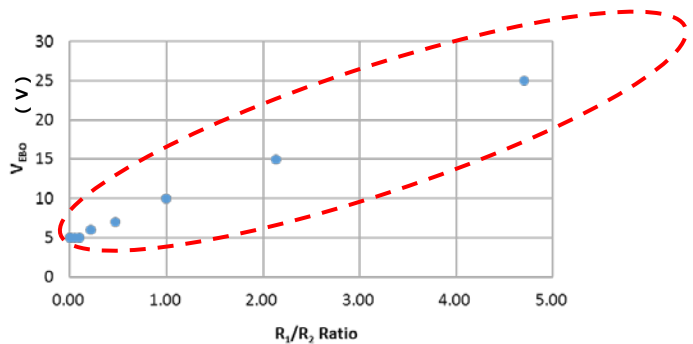

Figure 3-7 Reverse control voltage

Figure 3-8 V_{EBO} vs. R_1/R_2

3.3. Control voltages (input voltage (ON) ($V_{I(ON)}$)) and input voltage (OFF) ($V_{I(OFF)}$))

In the case of a bipolar transistor, the base current begins to flow at the threshold voltage (V_b) of roughly 0.6 V, causing the transistor to switch on or off. When a switch circuit is configured using a BRT as shown in Figure 3-1, the input voltage (V_I) at which Q begins to turn on is inversely proportional to R_2 and proportional to R_1, as indicated by the following equations:

$V_{be} = R_2/(R_1+R_2) * V_I$

$V_I = (R_1+R_2)*V_{be}/R_2 = (R_1/R_2 + 1)*V_{be}$

The input voltage (ON) and input voltage (OFF) of a BRT are defined as follows: (Ta=25°C)

• Input voltage (ON), $V_{IN(ON)}$:   Voltage required to obtain the collector current equal to or higher than the prescribed value (e.g., $I_C = 5$ mA) at $V_{CE} = 0.2$ V

• Input voltage (OFF), $V_{IN(OFF)}$: Voltage required to keep the collector current equal to or lower than the prescribed value (e.g., $I_C = 0.1$ mA) at $V_{CE} = 5$ V

Since BRTs are used in the saturation region as described above, minority carriers accumulate in the base region after the internal bipolar transistor turns on before they enter the saturation region. BRTs do not switch off until the accumulated minority carriers are swept out of the base region.

The current to charge and discharge the base is constrained by R_1 at turn-on. R_1 and R_2 have different effects on even BRTs with the same resistor ratio (R_1/R_2). Figure 3-9 plots the maximum $V_{I(ON)}$ values shown in datasheets.
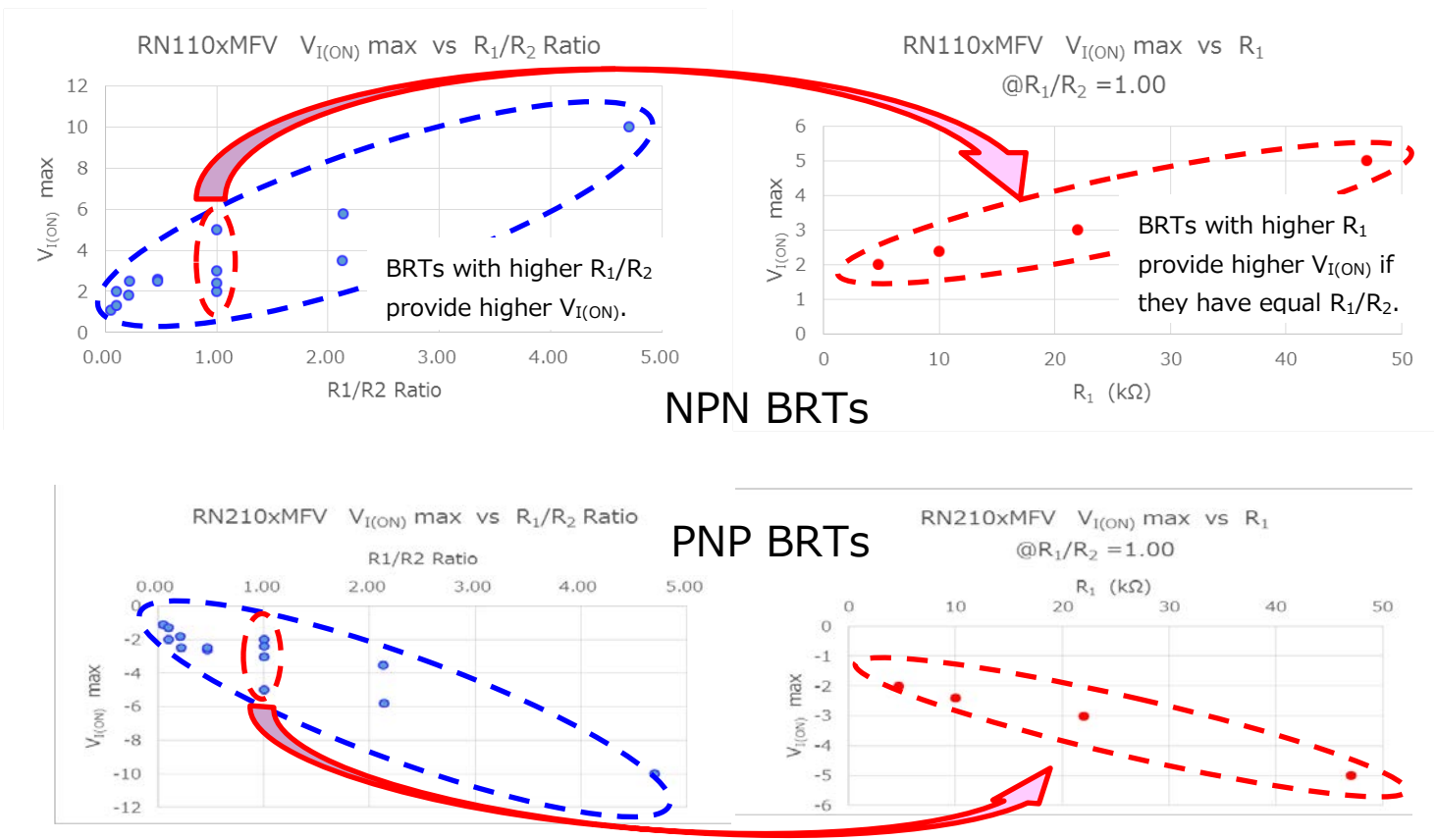

Figure 3-9 Effects of bias resistors on $V_{I(ON)}$

3.4. Switching times

The switching times of the bipolar transistor are defined as shown in Figure 3-10.

Turn-on time = delay time (t_d)   + rise time (t_r)

Turn-off time = storage time (t_{stg}) + fall time (t_f)

In the case of bipolar transistors, the accumulation of charge (Q_B) in the base region begins immediately upon turn-on. BRTs, which are operated in the saturation region, continue accumulating excessive charge even after they turn on. Charge accumulation lasts until ($\tau_n * I_b$), a value that is determined by the lifetime (τ_n) and base current (I_b) of the internal bipolar transistor.

At turn-off, BRTs remain on for a period of t_{stg} until the excessive charge accumulated after turn-on is swept out of the base region. Thereafter, I_B decreases exponentially.

Table 1 shows examples of the results of measurements of these BRT characteristics. The measurements were taken at a V_{CC} of 5 V, switching the input voltage from 0 V to 5 V and vice versa. The load resistance (R_L) is 1 kΩ. As indicated in Table 3-1, t_{stg} constitutes a dominant portion of the switching time.

Table 3-1 Examples of the results of measurements of BRT switching times

Type	R_1 (kΩ)	R_2 (kΩ)	t_r (ns)	t_{stg} (µs)	t_f (µs)
RN1401	4.7	4.7	38	1.89	0.11
RN1402	10	10	60	2.25	0.13
RN1403	22	22	118	2.41	0.21
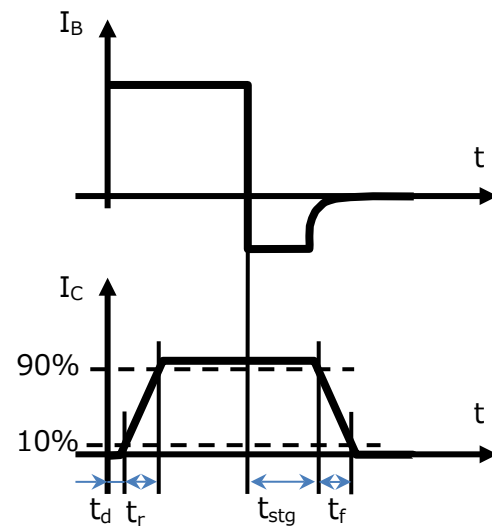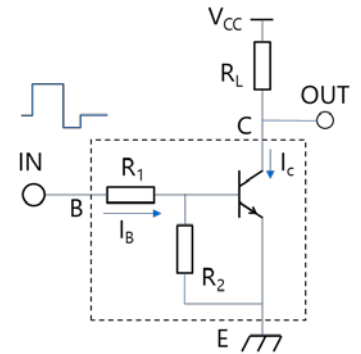
Figure 3-10 Test circuit for and definitions of switching times

There are two considerations for reducing t_{stg}:

1. Minimize the accumulation of excess carriers.

This helps reduce the saturation depth of the BRT while it is on. Shallow saturation means high h_{FE}. As can be seen from Figure 3-11, the collector current of a BRT depends mainly on supply voltage (V_{CC}) and load resistance (R_L). $V_{CE(sat)}$ contributes less to the collector current. Therefore, even if I_B is decreased and h_{FE} is increased, the effect on the output voltage can often be ignored. When priority is given to switching time, it is advantageous to select a BRT with a large R_1

Table 3-2 Effects of R_1 on t_{stg}

t_{stg} (µs)	R_1 (kΩ)	R_2 (kΩ)
1.84	47	47
2.81	22	47
3.36	10	47
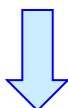
2. Remove excess carriers quickly.

Excess carriers accumulated in the base region are removed mainly through R_2 although the carrier removal path slightly differs depending on the configuration of the preceding circuit. (R_1 has a great influence on the saturation depth as described in 1. When R_1 is large, there are few excess carriers, which is advantageous for the emission time.). Therefore, BRTs with a low R_2 value are suitable for increasing the switching speed.

Table 3-3 Effects of R_2 on t_{stg}

t_{stg} (µs)	R_1 (kΩ)	R_2 (kΩ)
1.34	47	22
1.84	47	47
2.25	10	10
3.36	10	47

$I_C = (V_{CC} - V_{CE(sat)}) / R_L$
$V_{CE(sat)}$ is negligibly smaller than V_{CC} and does not affect I_C.
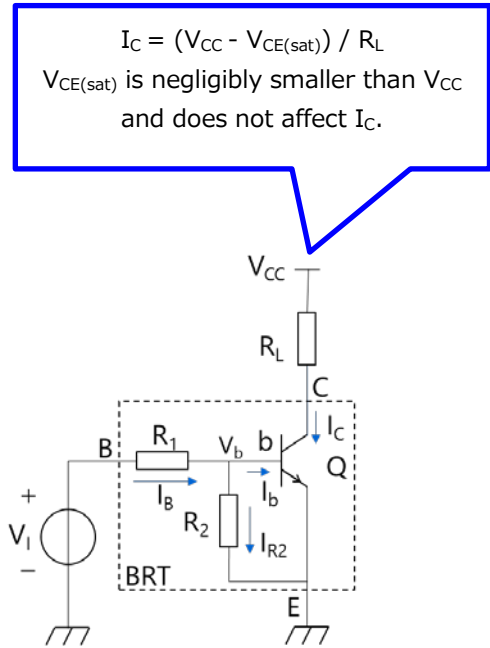

Figure 3-11 Collector current

4. Types of BRTs

Table 4-1 shows the lineup of single BRTs. Toshiba offers BRTs with many resistor combinations so that you can find one that satisfies your electrical characteristics requirements.

Toshiba also offers 2-in-1 BRTs shown in Figure 4-1.

Table 4-1 Lineup of single BRTs

Package dimensions (unit: mm)

$|V_{CEO}|$ (V)	$|I_C|$ (mA)	R1 (typ.) (kΩ)	R2 (typ.) (kΩ)	VESM (SOT-723) 1.2x1.2 NPN	VESM PNP	SSM (SOT-416) 1.6x1.6 NPN	SSM PNP	USM (SOT-323) 2.0x2.1 NPN	USM PNP	S-Mini (SOT-346) 2.9x2.5 NPN	S-Mini PNP
				Part Number							
50	100	4.7	4.7	RN1101MFV #	RN2101MFV #	RN1101 #	RN2101 #	RN1301 #	RN2301 #	RN1401 #	RN2401 #
		10	10	RN1102MFV #	RN2102MFV #	RN1102 #	RN2102 #	RN1302 #	RN2302 #	RN1402 #	RN2402 #
		22	22	RN1103MFV #	RN2103MFV #	RN1103 #	RN2103 #	RN1303 #	RN2303 #	RN1403 #	RN2403 #
		47	47	RN1104MFV #	RN2104MFV #	RN1104 #	RN2104 #	RN1304 #	RN2304 #	RN1404 #	RN2404 #
		2.2	47	RN1105MFV #	RN2105MFV #	RN1105 #	RN2105 #	RN1305 #	RN2305 #	RN1405 #	RN2405 #
		4.7	47	RN1106MFV #	RN2106MFV #	RN1106 #	RN2106 #	RN1306 #	RN2306 #	RN1406 #	RN2406 #
		10	47	RN1107MFV #	RN2107MFV #	RN1107 #	RN2107 #	RN1307 #	RN2307 #	RN1407 #	RN2407 #
		22	47	RN1108MFV #	RN2108MFV #	RN1108 #	RN2108 #	RN1308 #	RN2308 #	RN1408 #	RN2408 #
		47	22	RN1109MFV #	RN2109MFV #	RN1109 #	RN2109 #	RN1309 #	RN2309 #	RN1409 #	RN2409 #
		4.7	∞	RN1110MFV #	RN2110MFV #	RN1110 #	RN2110 #	RN1310 #	RN2310 #	RN1410 #	RN2410 #
		10	∞	RN1111MFV #	RN2111MFV #	RN1111 #	RN2111 #	RN1311 #	RN2311 #	RN1411 #	RN2411 #
		22	∞	RN1112MFV #	RN2112MFV #	RN1112 #	RN2112 #	RN1312 #	RN2312	RN1412 #	RN2412 #
		47	∞	RN1113MFV #	RN2113MFV #	RN1113 #	RN2113 #	RN1313 #	RN2313	RN1413 #	RN2413 #
		1	10	RN1114MFV #	RN2114MFV #	RN1114 #	RN2114	RN1314 #	RN2314	RN1414 #	RN2414 #
		2.2	10	RN1115MFV #	RN2115MFV #	RN1115 #	RN2115 #	RN1315 #	RN2315 #	RN1415 #	RN2415 #
		4.7	10	RN1116MFV #	RN2116MFV #	RN1116 #	RN2116 #	RN1316 #	RN2316	RN1416 #	RN2416 #
		10	4.7	RN1117MFV #	RN2117MFV #	RN1117	RN2117	RN1317	RN2317	RN1417 #	RN2417 #
		47	10	RN1118MFV #	-	RN1118	-	RN1318	RN2318	RN1418 #	RN2418 #
		1	∞	RN1119MFV #	RN2119MFV #	-	-	-	-	-	-
		100	100	RN1130MFV #	RN2130MFV #	-	-	-	-	-	-
		100	∞	RN1131MFV #	RN2131MFV #	-	-	-	-	-	-
		200	∞	RN1132MFV #	RN2132MFV #	-	-	-	-	-	-

AEC-Q101-qualified

$|V_{CEO}|$ (V)	$|I_C|$ (mA)	R1 (typ.) (kΩ)	R2 (typ.) (kΩ)	SOT23 (SOT-23) 2.9x2.4 NPN	PNP
				Part Number	
50	100	4.7	4.7	TDTC143E	TDTA143E
		10	10	TDTC114E	TDTA114E
		22	22	TDTC124E	TDTA124E
		47	47	TDTC144E	TDTA144E
		2.2	47	TDTC123J	TDTA123J
		4.7	47	TDTC143Z	TDTA143Z
		10	47	TDTC114Y	TDTA114Y

$|V_{CEO}|$ (V)	$|I_C|$ (mA)	R1 (typ.) (kΩ)	R2 (typ.) (kΩ)	S-Mini (SOT-346) 2.9x2.5 NPN	PNP
				Part Number	
50	800	1	1	RN1421	RN2421
		2.2	2.2	RN1422	RN2422
		4.7	4.7	RN1423	RN2423
		10	10	RN1424	RN2424
		0.47	10	RN1425	RN2425
		1	10	RN1426	RN2426
		2.2	10	RN1427	RN2427

The 2-in-1 BRTs are available in five-pin common-emitter, six-pin point-symmetrical, and parallel configurations.

Most 2-in-1 BRTs consist of an NPN or PNP pair, and parallel 2-in-1 BRTs also have the NPN/PNP configuration.
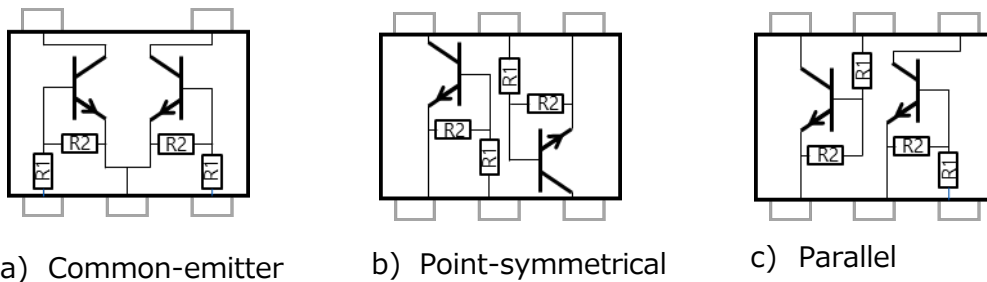

a) Common-emitter   b) Point-symmetrical   c) Parallel

Figure 4-1 2-in-1 BRTs

5. Selection guidelines

In most cases, BRTs are used as switches. Therefore, let's assume the use of BRTs as switches. Considerations for BRTs include the following:

1. Compatibility with the control circuit at the previous stage (selection of an NPN or PNP BRT)
2. Turning on and off the transistor without fail via a control signal ($V_{I(ON)}$ and $V_{I(OFF)}$ voltages)
3. Obtaining necessary voltage when the transistor is on (i.e., reducing a drop in the collector-emitter voltage in the "on" state)

4. Reducing the turn-on or turn-off time (i.e., increasing the switching speed)
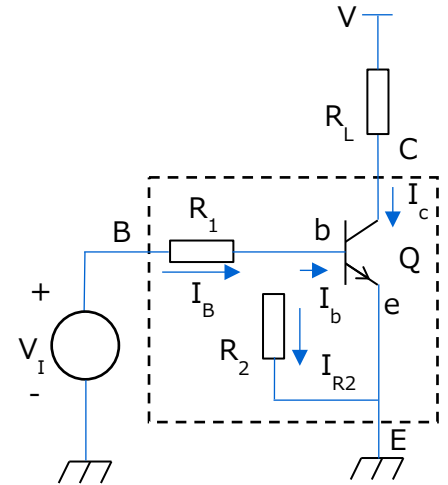
Figure 5-1 Basic circuit

These considerations are explained below using the basic circuit with an NPN BRT shown in Figure 5-1 (which is the same as the one shown in Figure 2-1). The BRT is enclosed in the dashed box. V_I is the control signal, V_{CC} is the supply voltage, and R_L is the load, including a pull-up resistor.

Each guideline for the selection of BRTs is discussed in the following subsections. Figure 5-2 shows the concepts of the electrical characteristics of BRTs.

Figure 5-2 Selection of electrical characteristics

5.1. Matching with the control circuit at the previous stage (selection of an NPN or PNP BRT)

Select either an NPN or PNP BRT according to the preceding control circuit. BRTs are often preceded by a circuit that can assume a high-Z state as shown in Figure 5-3. Use an NPN BRT if the output of the preceding circuit has a pull-down resistor. Use a PN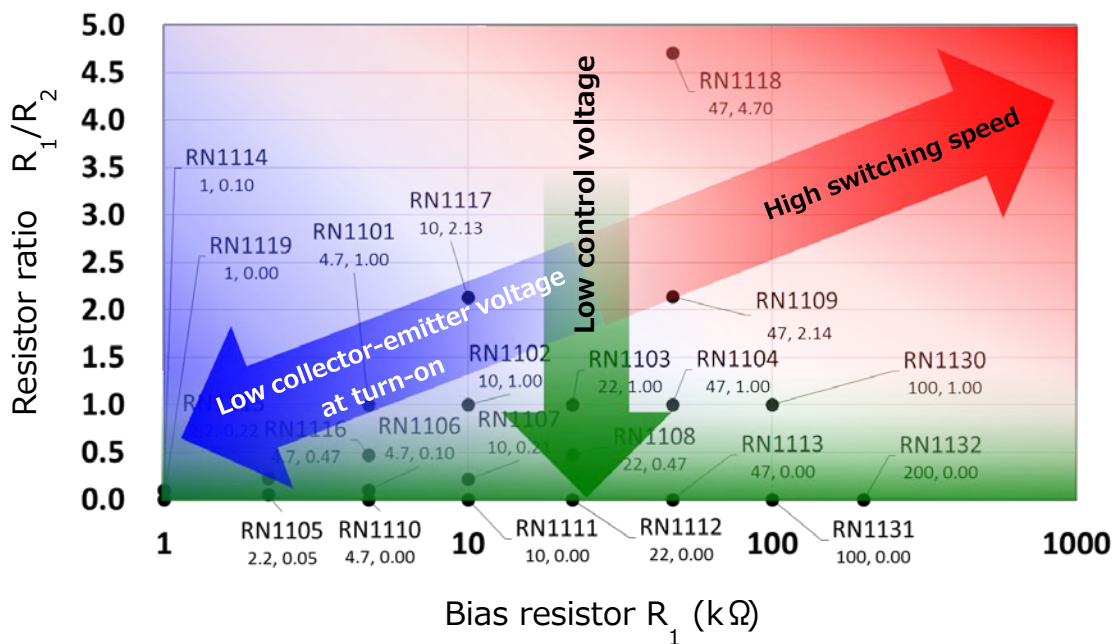P BRT if it has a pull-up resistor. Using the wrong type of BRT might, as shown in Figure 5-4, cause a BRT to malfunction at the midpoint potential between the pull-up resistor and the built-in bias resistors when the output of the preceding circuit is in the high-Z state.

Do not connect multiple NPN and PNP BRTs in parallel as shown in Figure 5-5 because the midpoint potential generated by each built-in bias resistor causes a malfunction.

$$V_I = \frac{R_1 + R_2}{R_{pullup} + R_1 + R_2}$$
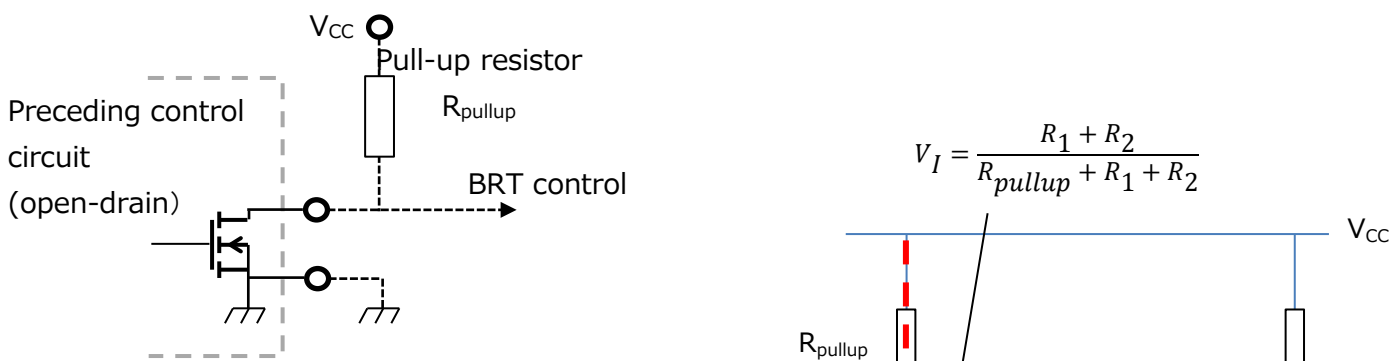
Figure 5-3 Circuit with a high-Z state preceding a BRT
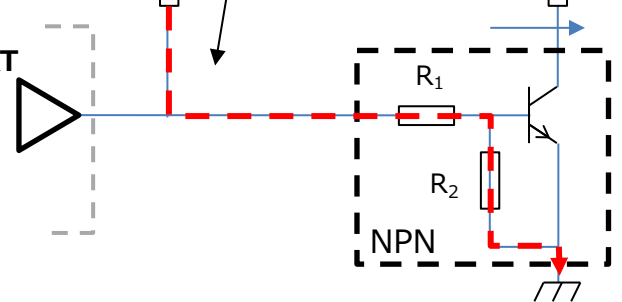
Figure 5-4 BRT preceded by pull-up resistor

$$V_I = \frac{R_{n1} + R_{n2}}{R_{p1} + R_{p2} + R_{n1} + R_{n2}}$$

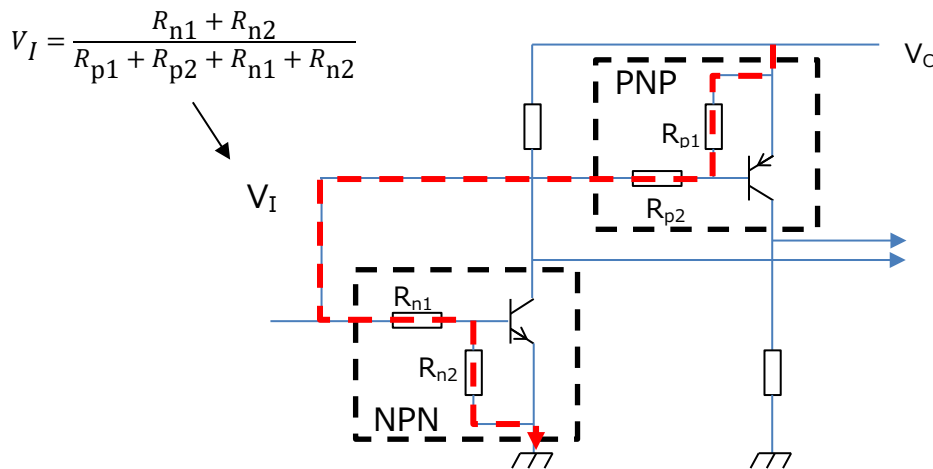**Figure 5-5 Connecting NPN and PNP BRTs in parallel**

5.2. Turning on and off the BRT without fail via a control signal ($V_{I(ON)}$ and $V_{I(OFF)}$ voltages)

Input voltage (ON) ($V_{I(ON)}$) and input voltage (OFF) ($V_{I(OFF)}$) are specified at 25°C in the datasheet. When designing a circuit, it is necessary to select BRTs that provide high-level V_I voltage of the control circuit at the previous stage higher than the maximum $V_{I(ON)}$ voltage and low-level V_I voltage lower than the minimum $V_{I(OFF)}$ voltage. Allow sufficient design margins according to the usage environment.

See Section 3.3, "Control voltages," for collector current (I_C) vs. input voltage (V_I) curves.

- BRTs with higher R_1/R_2 provide higher $V_{I(ON)}$.
- BRTs with higher R_1 provide higher $V_{I(ON)}$ if they have equal R_1/R_2.

5.3. Obtaining necessary output voltage when the BRT is on

(Reducing a drop in the collector-emitter voltage in the "on" state)

For example, when the NPN BJT turns on in the saturation region, the collector voltage drops to the GND level because of an external resistor (R_L) and the collector current (I_C). In practice, however, there is a voltage level called collector-emitter saturation voltage ($V_{CE(sat)}$) between the collector and GND (emitter) potentials. $V_{CE(sat)}$ can be reduced to some extent by increasing the base current (I_B).

I_b can be expressed as follows using V_I. This equation indicates that I_b can be increased by using a BRT with the following two conditions.

$$I_b = I_B - I_{R2} = (V_I - V_{be}) / R_1 - V_{be} / R_2$$

- Small R_1 value
- Large R_2 value

Such BRTs pass a greater current to the base at a given input voltage (V_I). For details on the input voltage, see Section 3.1, "Voltage across switch terminals at turn-on ($V_{CE(sat)}$)."

5.4. Reducing the turn-on or turn-off time

(Increasing the switching speed)

Storage time (t_{stg}) constitutes a dominant portion of the switching time because of the charge accumulated in the base region. Therefore, switching speed can be reduced by reducing the amount of charge accumulated in the base region and increasing the speed at which it is discharged. Select BRTs, taking the following points into consideration. For details, see Section 3.4, "Switching times." This requirement contradicts the description in Section 5.3.

- Do not bring a BRT into a deeper saturation level than is necessary.
  ⇒ Large R_1 value
- Reduce the impedance of the path through which excess carriers are removed.
  ⇒ Small R_2 value

Select a BRT with a small R_2 value because excess carriers are removed mainly through R_2. Excess carriers also disappear as a result of carrier recombination in the base region. There is a limit to a reduction in t_{stg} through carrier discharging.

6. Calculating the power dissipation of a BRT

For example, in amplifiers, bipolar transistors are used at high h_{FE}, causing the collector power dissipation ($V_{CE} * I_C$) to be dominant. In contrast, BRTs are commonly used at an h_{FE} of 10 to 20. Therefore, other sources of power dissipation cannot be ignored. It is necessary to consider the sum of the power dissipation of the internal bipolar transistor (Q) and bias resistors (R_1 and R_2) of a BRT.

The following shows a simple calculation example. Notice that bias resistor R_1 causes the greatest power dissipation.

Suppose that the BRT is the RN1402 ($R_1=R_2=10$ kΩ), the input voltage (V_I) is 10 V, the collector-emitter voltage (V_{CE}) is 0.2 V, the base-emitter voltage (V_{be}) is 0.7 V, and the operating current gain (h_{FE}) of the internal bipolar transistor is 10.

The BRT is enclosed by a dashed box in Figure 6-1. Let's calculate the amounts of currents indicated in the dashed box.

$$I_B = (V_I - V_{be}) / R_1 = (10 \text{ V} - 0.7 \text{ V}) / 10 \text{ k}\Omega \qquad = 0.93 \text{ mA}$$
$$I_{R2} = V_{be} / R_2 = 0.7 \text{ V} / 10 \text{ k}\Omega \qquad = 0.07 \text{ mA}$$
$$I_b = I_B - I_{R2} = 0.93 \text{ mA} - 0.07 \text{ mA} \qquad = 0.86 \text{ mA}$$
$$I_C = I_b * h_{FE} = 0.86 \text{ mA} * 10 \qquad = 8.60 \text{ mA}$$

Let the power dissipation of R_1 and R_2 be P_{R1} and P_{R2} respectively and the collector-emitter and base-emitter power dissipation of the bipolar transistor be P_{CE} and P_{be} respectively.

$$R_1 : P_{R1} = (V_I - V_{be}) * I_{R1} = (10 \text{ V} - 0.7 \text{ V}) * 0.93 \text{ mA} \quad = 8.65 \text{ mW}$$
$$R_2 : P_{R2} = V_{be} * I_{R2} = 0.7 \text{ V} * 0.07 \text{ mA} \quad = 0.05 \text{ mW}$$
$$V_{CE} : P_{CE} = V_{CE} * I_C = 0.2 \text{ V} * 8.6 \text{ mA} \quad = 1.72 \text{ mW}$$
$$V_{be} : P_{be} = V_{be} * I_b = 0.7 \text{ V} * 0.86 \text{ mA} \quad = 0.60 \text{ mW}$$

Hence, the power dissipation (P) of the BRT is calculated as:
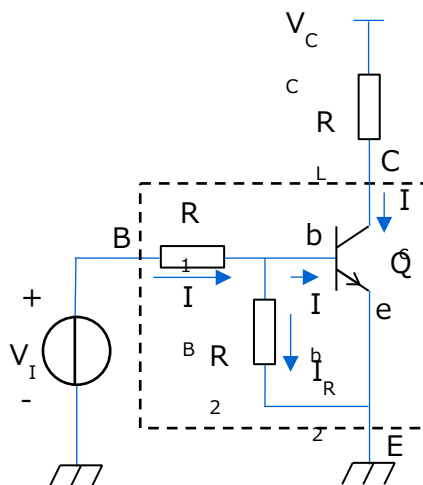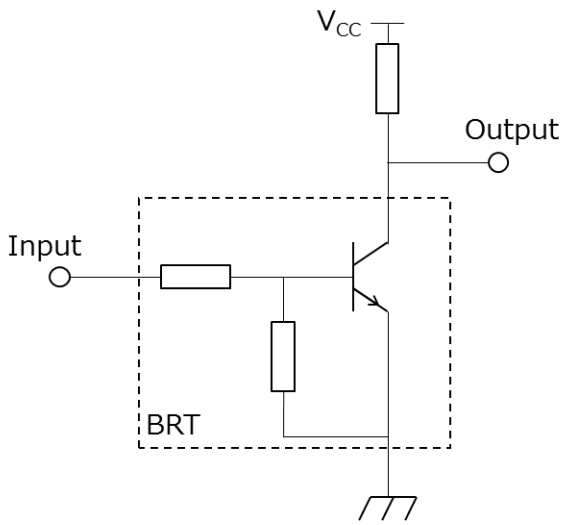$$P = P_{R1} + P_{R2} + P_{CE} + P_{be} \qquad = 11.02 \text{ mW}$$

Figure 6-1 Basic circuit

7. Application circuit examples

(a) Inverter circuit
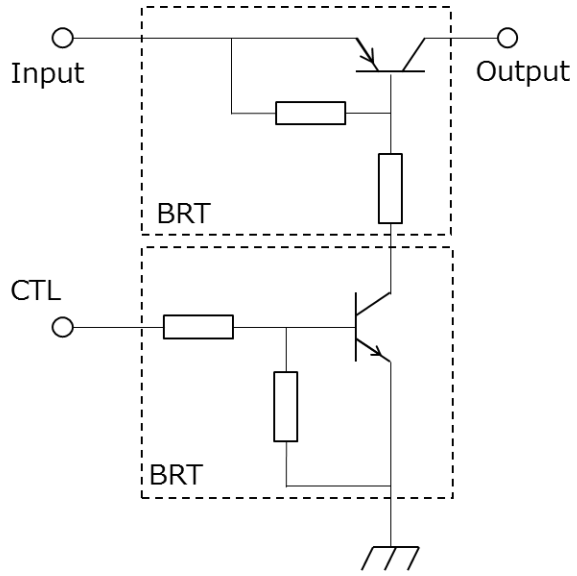
(b) Load switch
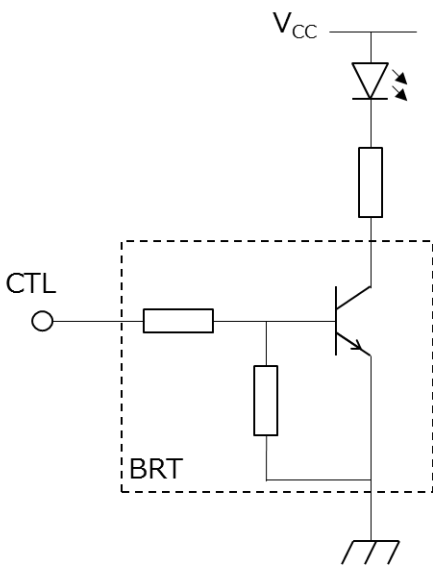
(c) LED driver circuit
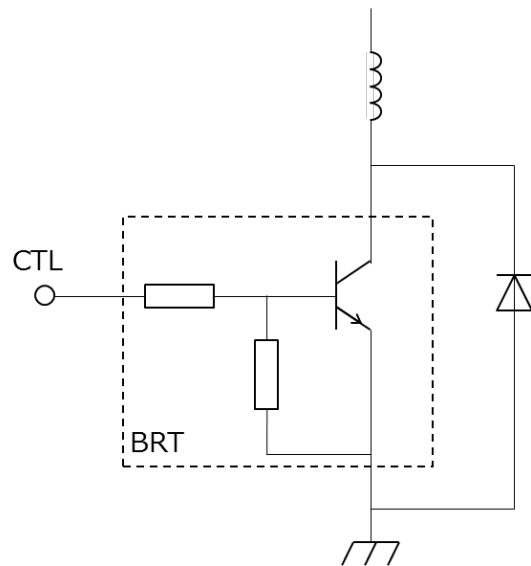
(d) Relay driver circuit
(Plunger control circuit)

Figure 7-1 BRT application circuit examples

For the lineup of BRTs → Click Here

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■Product Line Ups（Parametric Search）   **Click**

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