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BISS transistors and MEGA Schottky rectifiers - improved technologies for discrete semiconductors

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Abstract	This application note provides detailed information on recent product developments in the area of bipolar transistors and Schottky rectifiers which enable the designer to save cost and to improve the performance of electronic circuits.

PHILIPS

Revision history

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Contact information

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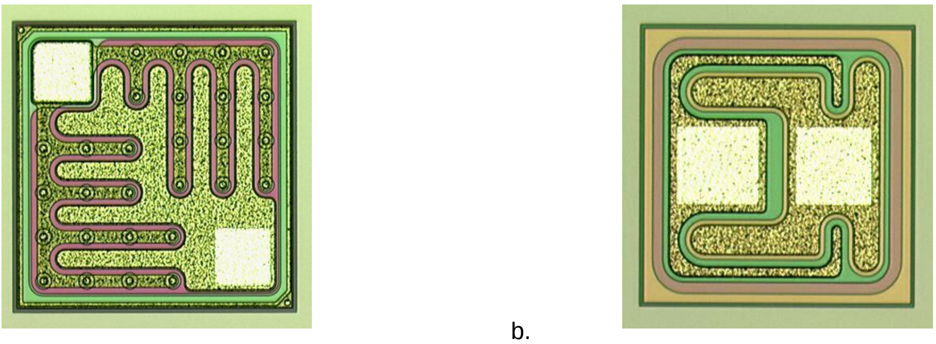
1. Introduction

Compared to integrated circuits, progresses in the development of discrete semiconductors are not well known. Optimized design results in lower loss and considerably improved thermal conductivity with discrete devices, as is demonstrated in the example of transistors with low collector-emitter saturation voltage and Schottky rectifiers with very low forward voltage drop.

The collector power dissipation $P_C = V_{CEsat} \times I_C$ is a major contributor to losses in bipolar transistors. Since the collector current I_C is predefined by the application, the device manufacturer has only the option to reduce the losses in the transistor by reducing the collector-emitter saturation voltage V_{CEsat}. With so-called low V_{CEsat} transistors, this is essentially achieved by the use of the mesh-emitter technology.

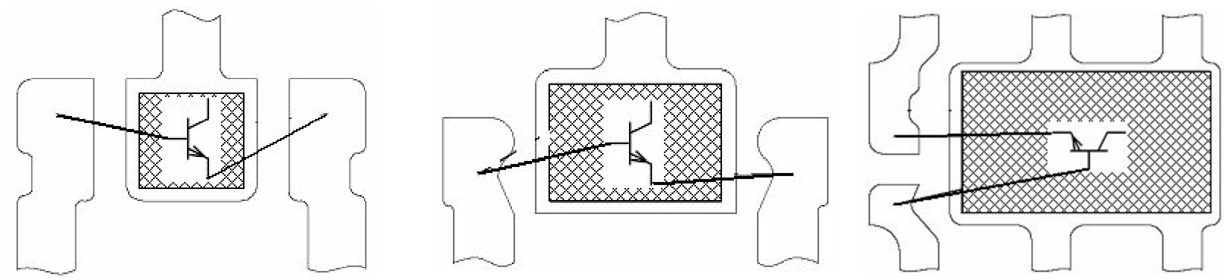
With the mesh-emitter design, the emitter series resistance is reduced by spreading the emitter region over a much larger area and by contacting it from the base as a mesh. This results in an evenly driven base, providing a more efficient use of the active emitter area on the die and thus a significantly lower collector-emitter saturation voltage (Fig 1).



a. b.

Fig 1. The die layout of a mesh-emitter transistor (a.) clearly shows the characteristic finger structure. Compared to the typical die layout of a conventional transistor (b.), a mesh-emitter transistor's finger structure and base contact holes provide a much larger active area.

Enlarging the die area within the limits provided by the respective package allows a further reduction of the occurring losses. The development of new lead frames and the use of 6pin packages (e.g. SOT457, SOT666) also allow a better heat dissipation (Fig 2).



a. b. c.

Fig 2. The standard lead frame of the SOT23 package (a.) limits the silicon area to about 0.5 mm^2. The lead frame of the SOT23 MaxSi (b.) permits to double the die area, and the SOT457 (c.) even provides a usable Si area of 1.85 mm^2.

2. Higher-performance transistors in smaller packages

The mesh-emitter technology has enabled the development of more powerful and, at the same time, smaller transistors that Philips identifies by the abbreviation BISS (Breakthrough In Small Signal). The comparison between the conventional 500 mA transistor BC817-40 in a SOT23 package and the BISS transistor PBSS4240V in a SOT666 package (Table 1:) clearly shows the advantages of the new design: smaller mounting surface, higher maximum collector current $I_{C\ max}$, higher maximum power dissipation P_{tot}, lower saturation voltage V_{CEsat} and higher current gain h_{FE} even at high collector current.

Table 1: The BISS transistors have a smaller footprint – with a 42 % smaller package size – while providing improved characteristics due to the mesh-emitter technology.

	BC817-40	**PBSS4240V**
Package	SOT23	SOT666
Mounting area	8.2 mm²	4.8 mm²
$I_{C\ max}$	0.5 A	2 A
$V_{CEO\ max}$	45 V	40 V
P_{tot}	0.25 W	0.3 W
$V_{CEsat\ max}$ at I_C = 0.5 A; I_B = 50 mA	700 mV	100 mV
$V_{CEsat\ max}$ at I_C = 2 A; I_B = 200 mA	–	400 mV
$h_{FE\ min}$ at I_C = 0.5 A	40	300

These improved characteristics of the mesh-emitter transistor PBSS4240V are the result of the combination and optimization of all parameters that were mentioned in the previous paragraph. For example, the voltage drop at I_C = 0.5 A is only 80 mV for the PBSS4240V, compared to 200 mV for the BC817 (Fig 3). Multiplication of these values by the collector current yields values for the collector dissipation of P_C = 40 mW compared to P_C = 100 mW, i.e. a reduction by 60 % due to the mesh-emitter design. The difference is even greater for the resulting temperature increase (ΔT = 17 K compared to ΔT = 50 K), since the lower heat transfer resistance R_{th} of the SOT666 package adds to the effect ($\Delta T = P_C \times R_{th}$).

Users can operate the BISS transistor at a higher ambient temperature without exceeding the maximum allowable die temperature of 150 °C, or they can benefit from the lower heat generation on the board. The lower power dissipation of the transistor also helps extend the operating time of battery-powered devices. To further reduce the power dissipation, transistors with lower V_{CE0} (e.g. 20 V) can be used, which provide an even lower collector-emitter saturation voltage (e.g. PBSS4320T).

Typical for bipolar transistors is the current gain drop at high collector currents. With mesh-emitter transistors, this characteristic is only present at significantly higher currents, due to their higher collector current capability. Fig 4 illustrates this in a comparison of the types mentioned above. At a collector current of I_C = 0.5 A, the current gain of the BC817-40 is already reduced to 34 % of its original value, while that of the much smaller PBSS4240V is still at 75 %. If the PBSS4350T is used (same package as BC817-40) the current gain is only reduced to 90 %.

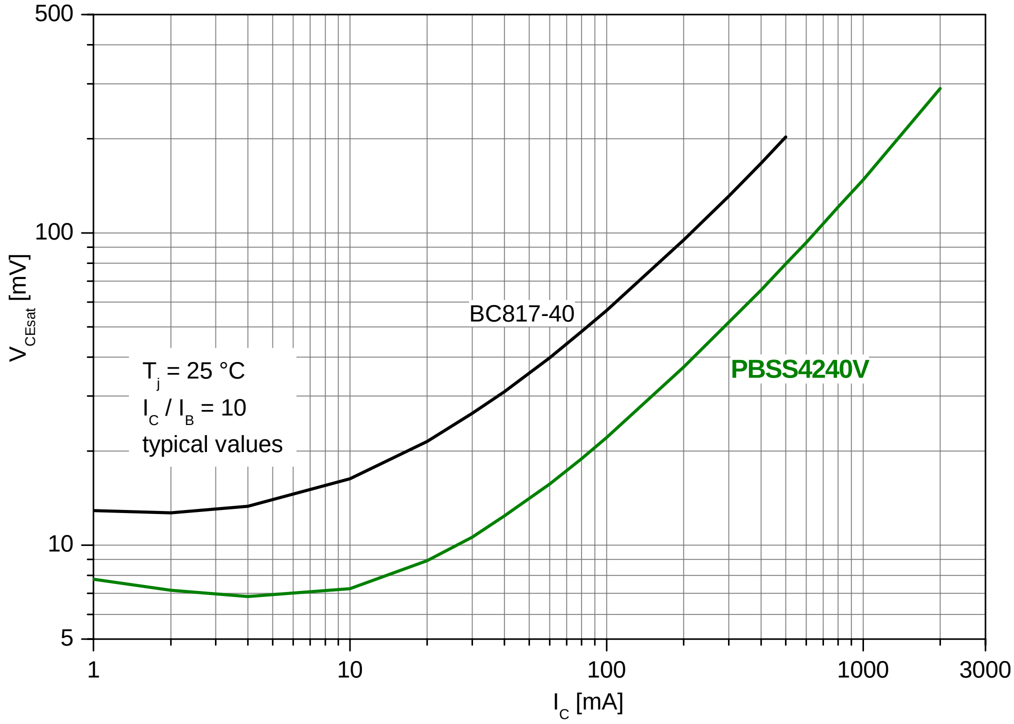


Fig 3. The reduced saturation voltage V_{CEsat} and the high collector current capability of the mesh-emitter transistor (PBSS4240V) as compared to a conventional transistor (BC817-40) enables 2 A continuous collector current and 70 mV collector-emitter saturation voltage in a SOT666 package comparable to 0603 resistors.

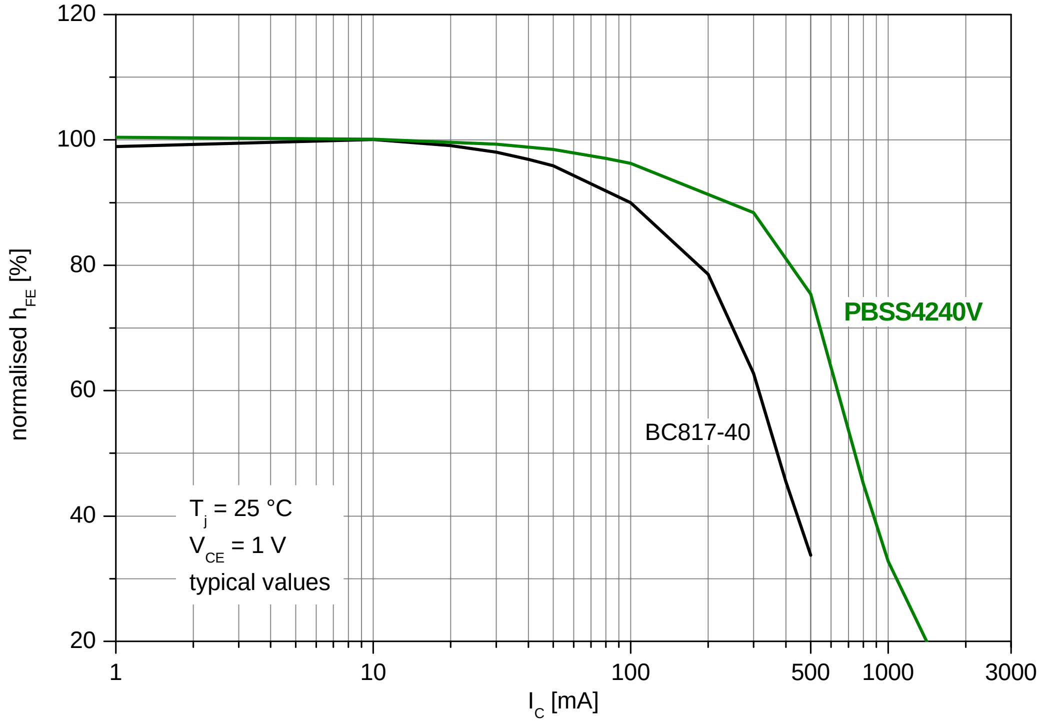


Fig 4. Mesh-emitter transistors (PBSS4240V) provide a higher current gain than conventional transistors (BC817-40).

3. BISS transistors in SOT23 package are comparable to medium power transistors

With conventional transistor designs, the die size that is often required for the necessary collector current limits further miniaturization. For example, transistors with collector currents > 0.5 A are not feasible in a SOT23 package using the traditional design. If, on the other hand, the mesh-emitter technology is used, transistors in this package can already provide collector currents of more than 2 A. Therefore, a mesh-emitter transistor (SOT23) can replace a much larger transistor in an SOT223 package at comparable or sometimes even better characteristics. Table 2: compares the BISS transistors PBSS4350T and PBSS4320T with a medium-power transistor BDP31.

Table 2: The much smaller BISS transistors in SOT23 packages can replace conventional medium power transistors whose package is more than five times larger (SOT223).

	BDP31	PBSS4350T	PBSS4320T
Package	SOT223 (SC-73)	SOT23	SOT23
Mounting area	46 mm²	8.2 mm²	8.2 mm²
$I_{C\ max}$	3 A	2 A	2 A
I_{CRP}	–	3 A	3 A
$V_{CEO\ max}$	45 V	50 V	20 V
P_{tot}	1.35 W	0.3 W	0.3 W
$V_{CEsat\ max}$ at I_C = 0.5 A; I_B = 50 mA	300 mV	80 mV	70 mV
$V_{CEsat\ max}$ at I_C = 2 A; I_B = 200 mA	700 mV	260 mV	210 mV
h_{FE} min at I_C = 2 A	20	200	200

A detailed curve of the collector-emitter saturation voltage of the three transistors is shown in Fig 5. The saturation voltage of the mesh-emitter transistors at a collector current of 1 A is about 40 % to 50 % lower than with a conventional transistor although it is driven only with 50 mA (I_C / I_B = 20) instead of 100 mA (I_C / I_B = 10). An SOT23 transistor requires less than 20 % board space than a SOT223 type. Mounted on a ceramic substrate, the power dissipation of a transistor in a SOT23 package can even be increased to 625 mW. Suitable alternatives are transistors in 6pin packages (e.g. SOT457) that can withstand a maximum power dissipation of 600 mW with a collector heatsink area of 1 cm².

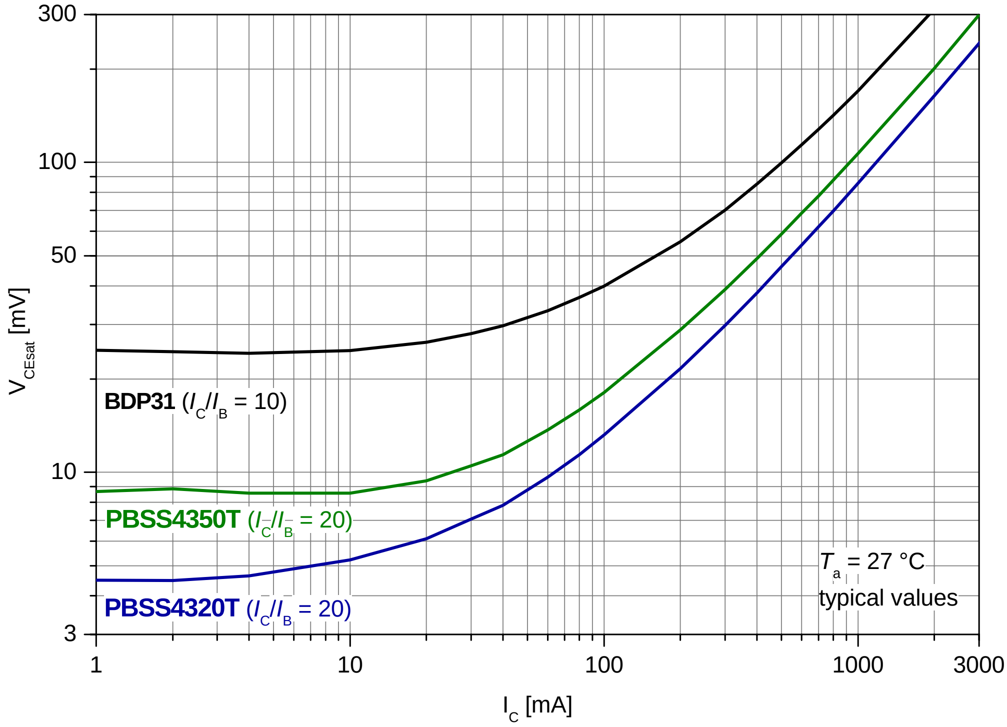


Fig 5. The reduced saturation voltage V_{CEsat} of the mesh-emitter transistor (PBSS-types) as compared to a conventional transistor (BC817) significantly reduces the collector power dissipation. Mesh-emitter transistors produce less heat, allow high collector currents and can therefore replace medium power transistors.

4. Transistors with low saturation voltage cost less

Since the overall costs of a transistor are largely influenced by the costs of its package, a transistor in a SOT23 package costs much less than a transistor in a bulkier SOT223 package. Users can further reduce costs by replacing expensive MOSFETs with mesh-emitter transistors. However, this will require some further considerations:

The resistance R_{CEsat}, which is obtained by dividing V_{CEsat} by I_C, is directly comparable to the on resistance $R_{DS(on)}$ of the MOSFET. But, a significant difference becomes obvious when comparing the drive modes: Bipolar transistors are current-controlled while MOSFETs are voltage-controlled, which results in some additional base power dissipation for the former ones. An advantage is the lower base-emitter saturation voltage of about 1 V, which is especially effective in the widely used circuits with supply voltages below 3.3 V. MOSFETs exhibit a higher $R_{DS(on)}$ at low gate-source voltages.

5. Application: Low-side switch

The advantages of higher efficiency, reduced temperature increase and available output voltage are demonstrated in the example of the low-side switch shown in Fig 6. The supply voltage V_{CC} is 3.3 V, the load current is $I_{Load} = I_C = 0.5$ A. The conventional transistor BC817 with the mesh-emitter transistor PBSS4320T, both in a SOT23 package are compared. The transistors are characterized by the values given in Table 1: and Table 2:.

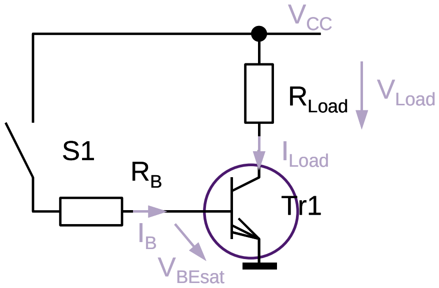


Fig 6. A smaller package, lower power dissipation, higher efficiency: BISS transistors offer advantages over the conventional transistors, as can be illustrated with this simple switch application.

The temperature increase ΔT is calculated from the total power dissipation P_{tot} and the heat transfer resistance R_{th}:

$$\begin{aligned}\Delta T &= P_{tot} \times R_{th}\\ &= (P_C + P_B) \times R_{th}\\ &= (V_{CEsat} \times I_C + V_{BEsat} \times I_B) \times R_{th}\end{aligned}$$

ΔT is calculated as 202 K for the transistor BC817 and as 38 K for the BISS transistor PBSS4320T, assuming standard mounting conditions without additional heatsink areas. At an ambient temperature of 25 °C, this means that the transistor BC817 cannot be used under these conditions because the maximum permitted junction temperature of 150 °C would be exceeded. While a larger collector heatsink area or the use of a medium-power transistor would solve the problem, it would also increase the costs. Thus, the better choice is the BISS transistor.

It is important for a number of applications that the available output voltage V_{Load} matches the supply voltage as closely as possible. V_{Load} is calculated as the difference between the supply voltage V_{CC} and the collector-emitter saturation voltage V_{CEsat} at only 2.6 V for the standard transistor BC817, compared to 3.23 V for the mesh-emitter transistor PBSS4320T.

The efficiency h results from the ratio of the load power P_{Load} and the supply voltage P_{CC}:

$$\begin{aligned}\eta &= P_{Load} / P_{CC}\\ &= [(V_{CC} - V_{CEsat}) \times I_C] / [V_{CC} \times (I_C - I_B)]\end{aligned}$$

While only a circuit efficiency of 72 % can be achieved using the standard transistor BC817, this increases to 89 % for the mesh-emitter transistor PBSS4320T. This very simple example shows how the use of transistors with low saturation voltage can improve key circuit parameters.

6. Less loss in Schottky rectifiers combined with reduced device size

With diodes, the forward power dissipation $P_F = I_F \times V_F$ is a major contributor to the overall loss. Since the diode current I_F is predetermined by the application, the diode manufacturer can only reduce the power dissipation by reducing the forward voltage drop (V_F). For Schottky rectifiers, the forward voltage V_F depends on the barrier level of the metal used and of the active area.

Reducing the forward voltage V_F by enlarging the active area conflicts with the requirement of miniaturization and increases the circuit losses due to the increased diode capacitance C_D. It should also be considered that the reverse current I_R will increase when the forward voltage decreases. For the development of its so-called MEGA (Maximum Efficiency General Application) Schottky rectifiers, Philips has therefore chosen the barrier so that either the forward voltage is minimized or the reverse current is minimized at a still low forward voltage level. Further, the die size area could be reduced to mount these rectifiers in advanced, very small low-signal packages (e.g. SOD323F, SOD523).

In order to further reduce the forward voltage, the thickness of the silicon die was reduced, and the ratio of die area and lead frame area was optimized.

7. Smaller package, same performance

Today, Schottky rectifiers in large packages such as SMA, SMB and SOD123 still dominate the market for currents between 0.5 A and 3 A. These are unreasonably bulky for applications such as Point-of-Load DC/DC converters. Now, the MEGA technology enables the development of rectifiers in smaller packages (SOD323F and SOD523) with forward currents of 0.5 A to 2 A.

Table 3: compares the key characteristics of the widely used diodes SS12 or SS14, respectively, to the new MEGA Schottky rectifiers PMEG1020EJ and PMEG2010EJ. The smaller SOD323F rectifiers either have a forward voltage that is similar to that of the SMA diode (PMEG2010EJ) or is significantly reduced (PMEG1020EJ). A comparison of the reverse currents is only possible to a limited degree because these are published for different reverse voltages, but still provides an impression of the order of magnitude.

Table 3: Despite providing similar characteristics as common Schottky diodes, the MEGA Schottky rectifiers require much smaller packages.

	SS12 / SS14	PMEG2010AEJ	PMEG1020EJ	PMEG6010AED
Package	SMA	SOD323F (SC-90)	SOD323F (SC-90)	SOT457 (SC-74)
Mounting area	18.3 mm²	4.4 mm²	4.4 mm²	10.7 mm²
$I_{F\,max}$	1 A	1 A	2 A	1 A
$V_{R\,max}$	20 V / 40 V	20 V	10 V	60 V
$V_{F\,max}$ at I_F = 1 A	500 mV	550 mV	350 mV	650 mV
$I_{R\,max}$	200 µA at $V_R = V_{R\,max}$	50 µA at V_R = 15 V	3000 µA at V_R = 10 V	350 µA at V_R = 60 V

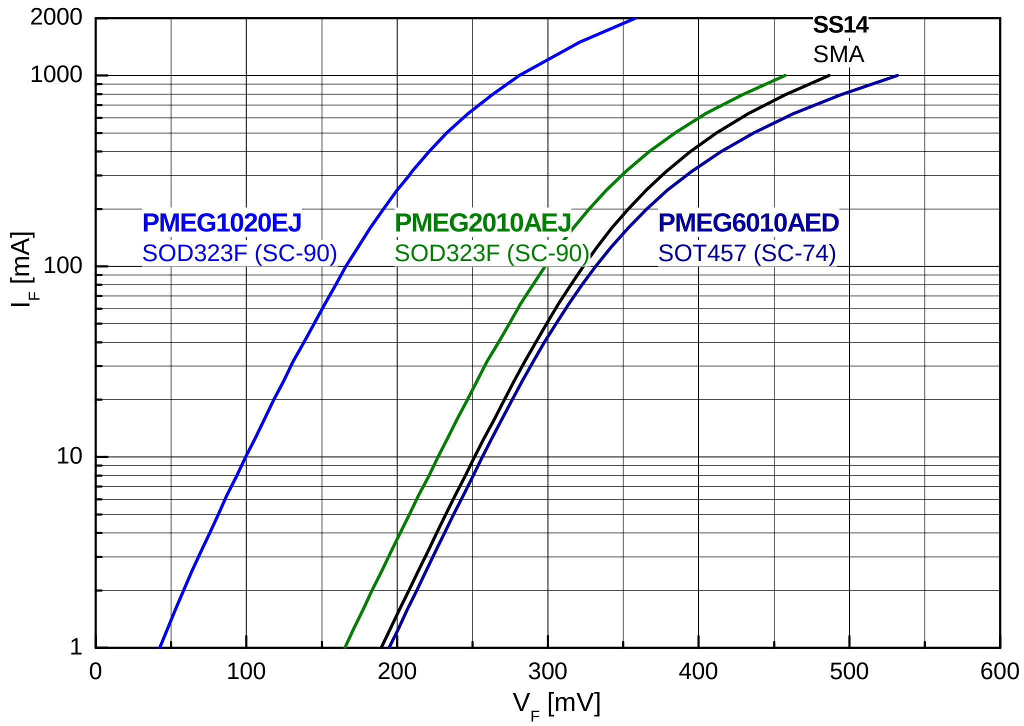


Fig 7. MEGA Schottky rectifiers (PMEG-types) are much smaller (SOD323F, SOT457) than conventional Schottky diodes (SS14 in SMA). The forward voltage V_F is equivalent or even lower.

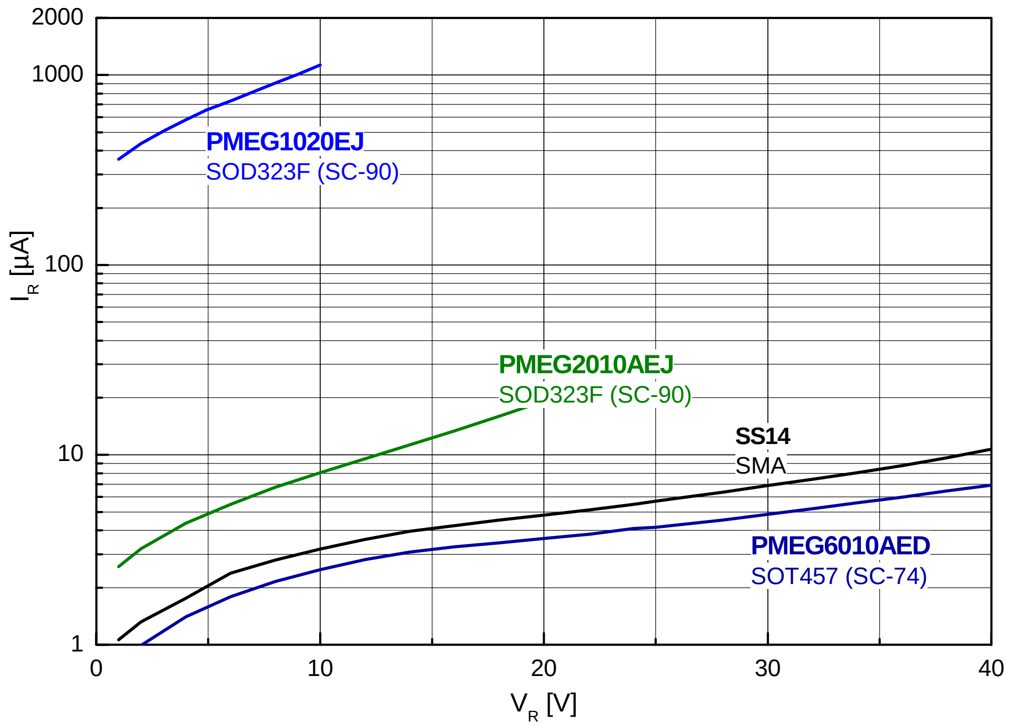


Fig 8. The reverse current I_R of the MEGA Schottky rectifier (PMEG-types) is in the same order of magnitude as with conventional Schottky rectifiers (SS14). Applications in which the reverse current is less critical can benefit from devices with extremely low forward voltage (PMEG1020EJ).

The characteristics in Fig 7 and Fig 8 show the typical forward and reverse behavior. The forward voltage V_F and the reverse current I_R of the PMEG2010EJ rectifier are similar to those of the SS12 and SS14 diodes. If an application requires an even lower forward voltage drop the MEGA Schottky rectifier PMEG1020EJ provides it, but at the expense of a higher reverse current. This makes this type attractive for applications with a relatively high duty cycle, i.e. a long on-time.

Some applications such as battery chargers require diodes with a reverse current that is as low as possible in order to prevent the battery from discharging via the charger when this is not connected to power. At the same time, losses in charging mode should be as low as possible. During the development of the PMEG6010AED rectifier, care was therefore taken to minimize the reverse current at a low forward voltage. Although this diode is mounted in the smaller SOT457 package, the forward voltage and the reverse current are equivalent to those of the SS12 and SS14 diodes in the SMA package (Table 3:).

8. Application: Reverse polarity protection diode and OR'ing

This simple circuit example of a reverse voltage protection diode in a battery-powered device compares a MEGA Schottky diode (PMEG1020EJ and PMEG2010AEJ) to a standard Schottky diode of the SS12 or SS14 type with respect to temperature increase, voltage drop and efficiency. It is assumed that the battery voltage in this example is 3 V, and the device's current consumption is 1 A.

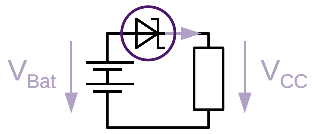


Fig 9. A MEGA Schottky rectifier offers the same performance than a SMA rectifier on 25 % board space.

The internal temperature rise ΔT is calculated by multiplying the forward power dissipation PF by the thermal resistance $R_{th\ j\text{-}s}$. The resulting values are about 17 K for the SS12, 19 K for the PMEG1020EJ and 30 K for the PMEG2010EJ.

Although the PMEG1020EJ rectifier is mounted in a much smaller package, its temperature increase is about the same to that of the much larger SMA diode, which is due to the lower forward voltage. The relatively high temperature increase of the PMEG2010AEJ is caused by the higher forward voltage combined with the higher thermal resistance of the much smaller package but is still admissible.

To use as much of the full battery voltage as possible, the voltage drop across the reverse polarity protection diode should be minimized. When the PMEG1020EJ rectifier is used, 2.65 V are available to supply the circuits, while about 2.5 V are available when the SS12 or PMEG2010AEJ rectifiers are used. The efficiency is calculated from the ratio of the operating voltage V_{CC} and the battery voltage V_{Bat} and is 88 % for the PMEG1020EJ, compared to about 82 % for the SS12 and PMEG2010AEJ rectifiers.

If several DC/DC converters shall be connected in series, these must be decoupled via diodes (OR'ing diodes). The above statements for reverse voltage protection diodes also apply to this application. In addition, the failure case "short-circuit on output" of a DC/DC converter should be considered: The associated diode will now operate under reverse conditions after heating up in forward direction. The resulting higher junction temperature significantly increases the reverse current. If, after making the switch, the reverse power dissipation $P_R = V_R \times I_R$ causes an additional temperature increase, the diode will be damaged due to thermal runaway. This can be prevented by reducing the thermal resistance R_{th} through the use of larger solder pads or by choosing a diode with a lower reverse current but with higher forward voltage. Therefore, the selection of the "right" diode – here PMEG1020 or PMEG2010 – will depend upon the decision whether the reverse current is still acceptable in a specific application.

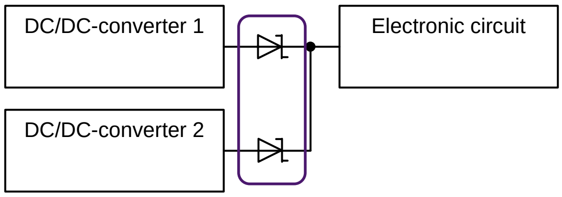


Fig 10. Using the lowest possible forward voltage drop requires careful observation of the resulting reverse current.

The MEGA Schottky rectifier diodes meet or even exceed the characteristics of much larger rectifiers. Users benefit from a better efficiency of the device due to lower losses and from a more space-efficient design due to the use of smaller packages.

9. Summary

Advances in design and improved packages made it possible to develop optimized discrete semiconductor devices, such as transistors with low saturation voltage and Schottky rectifiers with very low forward voltage, that meet today's increased requirements for end products in terms of heat generation, efficiency, space and costs. They are preferred solutions for use in portable, battery-powered devices (e.g. notebook PCs, digital cameras) as well as in automotive applications for load switching and in power supply systems.

10. Annex

Structure of a bipolar transistor

A bipolar transistor is built up from three different layers: a highly doped emitter layer, the medium doped base area and a low doped collector area. The entire transistor is built in the epitaxial layer. The highly doped substrate serves as a lead frame and low-impedance conductor. During the assembly process of the die in the lead frame, it must be noted that the backside is electrically active, contrary to ICs. The die is connected to the lead frame by eutectic soldering or conductive gluing. Bond wires connect the base and emitter contacts to the corresponding leads (Fig 11).

Saturation

A bipolar transistor is saturated when the collector-emitter voltage V_{CE} is lower than or equal to the base-emitter voltage V_{BE}. The condition of $V_{CE} < V_{BE}$ can be easily met in the emitter circuit but not in the collector circuit due to the fact that the base voltage can usually not exceed the collector voltage, which is equal to the supply voltage. The current gain I_C / I_B that is forced by the external circuitry is lower than the DC current gain h_{FE}. The collector current IC will only increase slightly with a higher base current I_B. The deeper the saturation, i.e. the smaller the ratio I_C / I_B, the lower will the collector-emitter saturation voltage V_{CEsat} be. A disadvantage is that the base power dissipation $P_B = V_{CEsat} \times I_B$ and the turn-off time t_{off} of the transistor will increase.

Structure of a Schottky diode

The Schottky diode consists of a medium doped epitaxial layer with a metallization. The resulting metal-to-silicon junction is characterized by a low forward voltage V_F and a short reverse recovery time t_{rr}. The guard ring forms a parasitic PN diode to prevent local magnification of field strength, significantly improving the forward breakdown performance. The highly doped substrate serves as lead frame and low-impedance conductor. Contrary to integrated circuits, the backside is electrically active, which requires a low-impedance connection between the die and the lead frame. This is implemented either by eutectic soldering or gluing. A bond wire connects the anode to the lead frame (Fig 12).

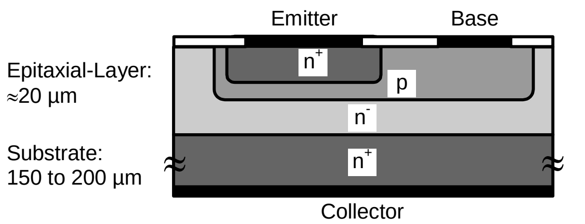


Fig 11. Bipolar transistor cross-section: The transistor is located in the epitaxial layer. As for diodes the much thicker substrate serves as carrier only.

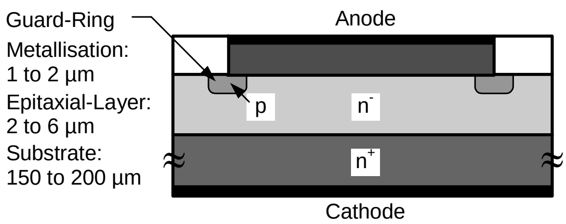


Fig 12. Schottky diode cross-section: The comprises of a metal alloy on a thin epitaxial layer. As for transistors the reverse side is electrically active.

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