Study of improved reverse recovery in power transistor incorporating universal contact

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Abstract

The improvement in reverse recovery of power NPN bipolar transistor (BJT) through incorporation of “universal contact” in the base is studied in detail. It is shown that use of universal contact allows redistribution of base current in saturation from collector region where recombination lifetime is high to extrinsic base region where effective recombination lifetime is low. The reverse recovery time decreases as collector current density increases but increases as collector breakdown voltage increases. The improvement in reverse recovery is accompanied with an increase in collector–emitter voltage in the ON state. For low voltage transistors and high voltage transistors at low collector current densities, the increase is primarily due to reduction in reverse current gain. For high breakdown voltage transistors, the use of universal contact results in early onset of quasi-saturation effect and results in degradation in ON state voltage at high collector current densities.

Keywords: Bipolar junction transistor; Semiconductor diode switches; Semiconductor device breakdown; Charge carrier lifetime; Current density; Charge carrier density

1. Introduction

Switching time and switching losses are primary concerns in high power applications. These two factors can significantly influence the frequency of operation and the efficiency of the circuit. Ideally, a high power switch should be able to turn-on and turn-off controllably and with minimum switching loss. Numerous semiconductor devices like GTO, BJT, MOSFET, IGBT and MCT have found application as switches in different ranges of blocking voltages and various advantages, and disadvantages have been observed with these devices in these ranges of operation. The bipolar junction transistor is an important power semiconductor device used in a wide variety of applications. The switching speed of a BJT is often limited by the excess minority charge storage in base and collector regions of the transistor during the saturation state. The conventional methods for improving the switching frequency by reducing the lifetime of the lightly doped collector region through incorporation of impurities such as Au, Pt or by introducing radiation-induced defects have been found unsuitable for high voltage devices due to increased leakage, soft breakdown and high ‘ON’ state voltage [1]. Among the techniques proposed to overcome these problems, use of universal contact [2] is particularly promising, as it does not require any additional processing of the wafer. To incorporate universal contact in a transistor only emitter mask needs to be redesigned [3] such that the emitter diffusion takes place not only in the emitter, but also in base contact region. Although encouraging results have been reported, a detailed investigation of these devices is still lacking. In the present work, a detailed study of the applicability of universal contact to BJT using a combination of analytical model,
numerical simulation and experimental work is described.

The paper has been divided into five sections. Section 1 gives the general introduction to the limiting mechanism of faster reverse recovery of BJT and the concept of "universal contact" to reduce reverse recovery. In Section 2, the analytical model for effective lifetime is developed and it is shown that reverse recovery tracks the effective lifetime. It is shown that one of the ways to reduce the effective lifetime is to increase the fraction of minority current injected into extrinsic base region by introducing a universal contact in that region. The dependence of effective lifetime on device parameters and effects of universal contact on transistor 'ON' state voltage are analyzed. In Section 3, the conventional transistor (S-I), and the transistor with universal contact incorporated in the extrinsic base (S-II) have been simulated for reverse recovery and \( I_{\text{C-}} V_{\text{CE}} \), effects. It is found that the simulation results broadly agree with the analytical results. In Section 4, the experimental results of reverse recovery, effect on \( V_{\text{CE(on)}} \) etc. are presented. Section 5 gives a brief summary of the effects of incorporation of universal contact on vital characteristics of BJT as a switch.

2. Analytical model

2.1. Effective lifetime

Fig. 1 shows a schematic of a conventional bipolar junction transistor (BJT), henceforth referred as S-I and Fig. 2 shows a typical reverse recovery waveform observed during switching of these transistors. The current waveform during the reverse transient phase can be quite complicated with several distinct features such as a constant current storage phase, falling current/rising voltage phase and decaying fall phase. The reverse recovery time \( (t_{\text{re}}) \) defined as the sum of constant collector current phase \( (t_{0} - t_{1}) \) called, storage time and 90% of fall time \( (t_{1} - t_{2}) \) after the base bias has been reversed, is intimately related to the effective minority carrier lifetime in the device defined as

\[
\tau_{\text{eff}} = \frac{Q}{I_{\text{B}}}
\]  

where \( Q \) is the total minority charge stored in emitter, base and collector regions and \( I_{\text{B}} \) is the base terminal current. As an example Fig. 3 shows a comparison of reverse recovery time for a BJT of breakdown voltage >1000 V with the effective minority carrier lifetime obtained using 2D numerical simulations of the transistor using the Silvaco simulation package [4]. The 2D simulations are based on drift-diffusion formalism and take into account the concentration dependent SRH recombination, concentration and field dependent mobility, band gap narrowing and Auger effects. It can be seen from Fig. 3 that the effective lifetime tracks reverse recovery time quite well so that it can be used as a simple and easy model parameter for study.

The effective lifetime can be related to other device parameters by noting that in the 'ON' state, the transistor is in saturation so that both the base-emitter and base-collector junctions are forward biased. As a result, minority charges are stored in emitter (\( Q_{\text{he}} \)), base (\( Q_{\text{hB}} \)) and collector (\( Q_{\text{hc}} \)) regions. Eq. (1) can be re-written as

\[
\tau_{\text{eff}} = \frac{Q_{\text{he}}}{I_{\text{B}}} \left(1 + \frac{Q_{\text{he}}}{Q_{\text{hC}}} + \frac{Q_{\text{hB}}}{Q_{\text{hC}}} \right)
\]

Since the doping in the emitter region is much higher as compared to doping in the collector region, \( Q_{\text{he}} \ll Q_{\text{hC}} \), so that Eq. (2) may be simplified to

\[
\tau_{\text{eff}} = \frac{Q_{\text{he}}}{I_{\text{B}}} \left(1 + \frac{Q_{\text{hB}}}{Q_{\text{hC}}} \right)
\]

If \( I_{\text{hC}} \) is the hole current injected into the collector, then

\[
Q_{\text{hc}} = \tau_{0} \times I_{\text{hC}}
\]

where \( \tau_{0} \) is the hole lifetime in the collector region. This allows Eq. (3) to be expressed as

\[
\tau_{\text{eff}} = \tau_{0} \frac{I_{\text{hC}}}{I_{\text{B}}} \left(1 + \frac{Q_{\text{hB}}}{Q_{\text{hC}}} \right)
\]

Since the doping in the base is often much higher than that in the collector and base width is also much smaller than collector thickness, it can be assumed that \( Q_{\text{hB}} \ll Q_{\text{hC}} \), so that

\[
\tau_{\text{eff}} = \tau_{0} \frac{I_{\text{hC}}}{I_{\text{B}}}
\]

Eq. (6) indicates that there are two ways of decreasing the effective minority carrier lifetime. One is by reducing the bulk lifetime \( \tau_{0} \), by introducing the lifetime killing elements Au, Pt etc. and the other is by reducing the fraction \( \left( \frac{I_{\text{hC}}}{I_{\text{B}}} \right) \) of current that results from recombination.
in the collector region. Eq. (6) can be cast into an alternative form by noting that the total base current $I_B$ can be expressed as sum of three components; hole current injected into the emitter, hole recombination current in base region and hole current injected into the collector. For transistors with moderate or high current gain, the component of current due to injection of holes into the emitter is much smaller than the other two components in saturation state so that, $I_B \approx I_{hB} + I_{hC}$.

This allows Eq. (6) to be re-written as

$$I_B/C18/C19 = I_{hB} + I_{hC}.$$  

Eq. (7) can be re-written in a more instructive form as

$$\frac{1}{\tau_{eff}} \cong \frac{1}{\tau_0} + \frac{1}{\tau_{hB}}.$$  

where $\tau_{hB} = \tau_0 \left( \frac{J_B}{J_{hB}} \right)$. Eq. (8) shows that effective lifetime can also be decreased by reducing the time constant $\tau_{hB}$ by increasing the hole recombination current into the base relative to hole current injected into the collector. The hole current in the base can be viewed as consisting of two components; one due to recombination in the intrinsic base region ($I_{hB}$) and the other due to

Fig. 2. Base and collector current waveforms during turn-off.

Fig. 3. A comparison of effective lifetime with reverse recovery of BJT of >1000 V.
recombination with electrons injected by the collector into the extrinsic base region \( (I_{hBx}) \). This allows the time constant \( \tau_{hB} \) to be decomposed into two components:

\[
\frac{1}{\tau_{hB}} \simeq \frac{1}{\tau_{hBi}} + \frac{1}{\tau_{hBx}} \quad (9)
\]

where \( \tau_{hBi} = \tau_0 \frac{I_{hBi}}{I_{hC}} \) is the lifetime in the intrinsic base and \( \tau_{hBx} = \tau_0 \frac{I_{hC}}{I_{hBx}} \) is the lifetime in the extrinsic base region.

The base current component \( I_{hBx} \) is normally small because of the small electron recombination velocity of the p'p base ohmic contact so that time constant \( \tau_{hBx} \) is large. However, if the p'p base contact is replaced by the n'p' universal contact as shown inside the base of the BJT of Fig. 4, henceforth called S-II the electron current injected into the extrinsic base is expected to increase considerably resulting in sharp decrease in \( \tau_{hBx} \) and the overall effective recombination lifetime.

This method of reduction in effective lifetime is similar to the improvement in reverse recovery obtained by connecting a Schottky diode externally between base and collector. The use of Schottky diode with lower turn-on voltage allows base current to be diverted from collector region of the transistor where recombination lifetime is high to the Schottky diode, which has zero effective minority carrier lifetime. In the present approach also, the base current is diverted from collector region to extrinsic base region where effective recombination lifetime is low due to presence of universal contact. Although the principle is essentially same, the present approach has the benefit of being applicable to high voltages and also promises to occupy less silicon area.

The discussion so far has brought about the importance of low value of the time constant \( \tau_{hBx} \) or equivalently the ratio \( \frac{I_{hB}}{I_{hBx}} \) for improving the effective lifetime.

![Fig. 4. (a) Bipolar junction transistor (S-II) including single emitter finger and two base fingers including universal contact, (b) doping profiles of low voltage transistor, (c) doping profiles of high voltage transistor.](image)
We next discuss the important factors that impact the ratio of hole current injected into the collector and the electron current injected into the extrinsic base region.

### 2.2. Dependence of effective lifetime on device parameters

Fig. 5 shows a 1D view of the device in the extrinsic base in the region where $n^+$ diffusion in p-diffused base as part of universal contact has been made. The $x_1$, $x_2$ and $x_3$ are the metallurgical junctions of $n^+ p$ “universal contact”, $p^+$ junction and back $n^+$ contact respectively. The $x_1$ and $x_2$ are the depletion edges of $n^+ p$ and $p^+$ junctions inside the p diffused region. Analogous to PIN [5] diode, the base–collector voltage ($V_{BC}$) in saturation can be expressed as the sum of three components as follows:

$$V_{BC} = V_{BC1} + V_{BC2} + V_{BC3}$$  \hspace{1cm} (10)

where $V_{BC1}$ is the voltage drop at $x_2$, $V_{BC2}$ is the voltage drop in the collector region in saturation and $V_{BC3}$ is the voltage drop at $x_3$.

The hole current, $I_{hBx}$, which is identical to the electron current injected by the collector into the base, can be expressed

$$I_{hBx} = \frac{q^2 n_i^2 D_n \exp \left( \frac{q V_{BC1}}{kT} \right)}{Q_p} \zeta (A_{BC} - A_E)$$  \hspace{1cm} (11)

where $A_{BC}$ is the base-collector area, and $A_E$ is the emitter area, $\zeta = \frac{A_{BC}}{A_E}$ is the fraction of extrinsic base area occupied by $n^+$ part of the “universal contact” and $A_N^+$ is the area of $n^+$ in the “universal contact”.

Defining a factor $n_B = \frac{f_{BC}}{Q_p}$, Eq. (11) may be written as

$$I_{hBx} = \frac{q^2 n_i^2 D_n \exp \left( \frac{q V_{BC}}{\eta_k kT} \right)}{f_{BC} \zeta (A_{BC} - A_E)}$$  \hspace{1cm} (12)

For simplicity, we assume that when junction is forward biased $x_2 = x_0$ and low level injection conditions prevail so that $Q_p = q \int_{x_1}^{x_2} N_s(x) dx$. To avoid reach-through breakdown prior to onset of avalanche breakdown, we require that at avalanche breakdown $(x_2 - x_1) > 0$. Taking $E_C$ as the critical field, we obtain the condition

$$\frac{q}{\eta_k} \int_{x_1}^{x_2} N_s dx > E_C \quad \text{or} \quad Q_p > e_s E_C$$  \hspace{1cm} (13)

Defining $f_{B} = \frac{Q_p}{e_s E_C}$, allows Eq. (12) to be re-written as

$$I_{hBx} = \frac{q^2 n_i^2 D_n \exp \left( \frac{q V_{BC}}{\eta_k kT} \right)}{f_{B} e_s E_C} \zeta (A_{BC} - A_E)$$  \hspace{1cm} (14)

The factor $f_B$ represents a safety factor in the sense that for $f_B > 1$, the charge $Q_p$ under the universal contact is large enough to prevent onset of reach-through prior to onset of avalanche breakdown. On the other hand if $f_B < 1$, then the reverse blocking voltage would be determined primarily by the occurrence of reach-through.

The minority carrier current $I_{hC}$ can be modeled as recombination current in the collector region and written as

$$I_{hC} = q n_i \frac{W_C}{\tau_0} \exp \left( \frac{q V_{BC}}{\eta_k kT} \right) A_{BC}$$  \hspace{1cm} (15)

![Fig. 5. A one-dimensional view of the transistor incorporating “universal contact” at A–A’ of Fig. 4.](image-url)
where \( \eta_c = \frac{n_{BC}}{n_{BC}^*} \) is the ideality factor of the recombination current in the collector region. The ratio \( I_{BE}/I_C \) can now be obtained using Eqs. (14) and (15) as

\[
\frac{I_{BE}}{I_C} = \frac{q n_D D_0}{W_C} \tau_0 \exp \left( \frac{q V_B C}{kT} \left( \frac{1}{\eta_B} - \frac{1}{\eta_C} \right) \right) \frac{1}{f_B s L_C} \frac{(A_{BC} - A_E)}{A_{BC}}
\]

(16)

The total base current \( J_B \) may be written in terms of its ideality factor \( n \) as

\[
J_B = J_0 \exp \left( \frac{q V_B C}{nkT} \right)
\]

(17)

Eq. (17) can be used to re-write Eq. (16) as

\[
\frac{I_{BE}}{I_C} = \frac{C_B \tau_0}{W_C} \frac{q^{2} V_B C}{f_B}
\]

(18)

where \( q V_B C = n \times n_{BC}^* \eta_{BC}^* \) and \( C_B = \frac{q n_D D_0}{\eta_B \eta_C^*} \eta_{BC}^* \frac{d_{BC}^* - d_{Bx}^*}{d_{BC}^*} \).

Substitution of Eq. (18) and corresponding value of \( \frac{n_{BC}^*}{\tau_{BC}^*} \) in Eq. (8), we obtain

\[
\frac{1}{\tau_{BC}^* \tau_{BC}^*} = \frac{1}{\tau_{hB}} + \frac{1}{\tau_{hB}}
\]

(19)

where \( \tau_{hB} = C_B i_{hBC}^{*} n_{BC}^* \). Eq. (19) can be used to explain several important features regarding the effective minority carrier lifetime and therefore the switching speed of the transistors with universal contact. For example Eq. (19) shows that the effective lifetime will decrease with increase in base or collector current density. The reason for this is due to the different ideality factors of the current injected into the collector and extrinsic base region. The minority hole current in the collector region increases as \( \exp(q V_B C/2kT) \) due to high level injection in the collector region, while the current injected into the base increases \( \exp(q V_B C/kT) \) due to low level injection condition, causing the ratio \( I_{BE}/I_C \) to increase with increase in bias or with increase in current density. Eq. (19) also indicates that the effective lifetime will increase as breakdown voltage increases. The reason for this is that increase in the breakdown requires increase of the thickness \( W_C \) of the collector region, which decreases the ratio of \( I_{BE}/I_C \). Eq. (19) also shows that a decrease in safety factor \( f_B \) will also improve \( I_{BE}/I_C \). In fact, may be made less than unity indicating onset of reachthrough prior to avalanche breakdown. This illustrates a new mechanism whereby the reverse blocking characteristics can be traded with the switching characteristics.

Along with reverse recovery time and breakdown voltage, the \( V_{CEtext{sat}} \) is another very important transistor characteristics. The insertion of universal contact in the extrinsic base region is expected to have significant influence on this parameter. A simple analysis of this effect on \( V_{CEtext{sat}} \) is presented in the next section.

2.3. Analysis of \( V_{CEtext{sat}} \), the ‘ON’ state voltage

The collector–emitter voltage in the ‘ON’ state can be expressed as

\[
V_{CEtext{sat}} = V_{CEtext{sat}}^{int} + I_C (R_C + R_E)
\]

(20)

where the first term represents the intrinsic collector–emitter voltage and the second term represents the voltage drop in the parasitic collector resistance \( R_C \) and the emitter resistance \( R_E \).

An expression for intrinsic collector–emitter voltage is easily obtained from Ebers–Moll model:

\[
V_{CEtext{sat}}^{int} = \frac{1}{\beta_f} \ln \left( \beta_f \right)
\]

(21)

where \( \beta_f \) and \( \beta_R \) are current gains in forward and reverse active modes respectively. \( I_C/I_B \) is the forced \( \beta \) in saturation. The insertion of universal contact in the extrinsic base region leaves the forward current gain \( \beta_f \) unchanged but reduces the reverse current gain \( \beta_R \). The change in inverse current gain \( \beta_R \) can be explained by noting that

\[
\beta_R = \frac{I_E}{I_B} \frac{I_C}{I_B} \frac{I_C}{I_C}
\]

(22)

Defining injection efficiency (\( \gamma_C \)) of the collector–base junction as

\[
\gamma_C = \frac{J_C}{J_{BC} + J_E}
\]

(23)

allows Eq. (22) to be re-written as

\[
\beta_R = \frac{A_E}{A_C} \frac{1}{\gamma_C} \frac{I_C}{I_E}
\]

(24)

where \( A_C \) is collector areas. Since the first two factors are same in the normal and modified transistor, Eq. (24) shows that the change in \( \beta_R \) is directly related to the ratio \( \frac{I_C}{I_E} \). This means that as the ratio \( \frac{I_C}{I_E} \) decreases due to the incorporation of universal contact, \( \beta_R \) will also be reduced leading to an increase in collector–emitter voltage in saturation. However, due to the logarithmic dependence of the voltage on current gain, the increase in voltage is expected to be small.

In the second term of Eq. (20), the contribution of the emitter resistance on the ‘ON’ state voltage would remain unchanged as a result of insertion of universal contact because the emitter resistance is unaffected. Similarly, in the absence of conductivity modulation in the collector region, the collector resistance would also remain unchanged. This would be true for transistors designed for low voltage operation where high-level injection condition in the collector may not occur.
ever, for high voltage transistors, high-level injection does occur and insertion of universal contact by altering current distribution is expected to result in a modification of collector resistance.

As long as high-level injection conditions prevail in the entire collector region, the collector resistance and the voltage drop across it remain small due to conductivity modulation. However, as collector current density (and therefore base current density for a constant $I_{CE}/I_B$ ratio) increases, the region where conductivity modulation occurs begins to shrink leaving behind a portion of high resistance collector layer [6]. The voltage drop across this neutral collector region result in a sharp increase in collector–emitter voltage. The voltage drop in unmodulated part of the collector region is given by

$$V_I = \frac{J_C(W_C - W_M)}{q\mu_nN_D}$$

(25)

The modulated portion of the collector region $W_M$, can be expressed as

$$W_M = \frac{2qD_np(0)}{J_C}$$

(26)

Since the hole density, $p(0)$, at the collector–base junction is directly proportional to recombination current in collector region, $J_{HC}$, Eq. (26) can be written as

$$W_M = a\frac{I_{HC}}{I_C}$$

(27)

Where '$a$' is a constant. Use of Eq. (27) allows Eq. (25) to be expressed as

$$V_I \propto \frac{J_C}{N_D} \left[ W_C - a\frac{I_B}{I_C} \times \frac{I_{HC}}{I_B} \right]$$

(28)

Eq. (28) is valid only after the unmodulated region of collector begins to form. This would occur when

$$\frac{I_{HC}}{I_B} < \frac{W_C}{aI_B/I_C}$$

(29)

Since the incorporation of “universal contact” results in a decrease in fraction of hole current injected into the collector, the sharp increase in collector–emitter voltage is expected to occur at lesser collector current density as compared to the conventional transistor.

The analytical models developed above provide insight into important factors affecting different characteristics of the transistor. The next section describes an elaboration of these results obtained using 2D numerical simulation of the transistors.

3. Simulation results

To study the effect of incorporation of “universal contact” on transistor’s characteristics, 2D numerical simulations were carried out. The simulations are based on drift-diffusion formalism and take into account concentration dependent SRH recombination, concentration and field dependent mobility, band gap narrowing and Auger effect. A transistor with inter-digitated base–emitter geometry was chosen for simulations. This configuration has large extrinsic base region where the universal contact could easily be incorporated. Two different kinds of BJT devices, one with relatively low BV$_{CBO}$ of $\sim$150 V and another with BV$_{CBO}$ exceeding 1000 V were chosen for study.

The description of the low voltage transistor including surface and bulk concentration, junction depths etc. are given in Table 1. Transistor geometry with half emitter finger width of 50 $\mu$m and a base finger width of 80 $\mu$m was taken. In structure S-II, universal contact was incorporated with a $n^+/p^+$ ratio of 1:1. The Gummel plots obtained from simulations were found to be identical for both the transistor structures with a current gain of 80 at a collector current density of 100 A/cm$^2$. This is expected because the universal contact in the extrinsic base region will make a difference only when the collector–base junction is forward biased. The switching characteristics of the two structures were simulated by abruptly switching the base voltage in such a way that the forward and initial values of reverse base currents were identical. Reverse recovery time was extracted from the waveforms of the collector/base currents and studied as a function of collector current density. In these simulations, the ratio of collector to base currents in the ON state was kept at a fixed value of 10. Fig. 6 shows a comparison of reverse recovery time for the two structures. The reverse recovery time decreases with increase in collector current density in

<p>| Table 1 |</p>
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<th>Details of parameters of simulated low voltage transistor</th>
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<td>Device</td>
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<td>Low voltage (100–155 V)</td>
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accordance with the predictions of the model developed earlier. The reverse recovery time of BJT S-II is significantly shorter than that of the conventional BJT S-I with an improvement of 62.2% at a collector current density of 1 A/cm² and 47% at about 100 A/cm². Effective minority carrier lifetime was also extracted from the simulations using the definition given in Eq. (1). The τeff for BJT S-II is lower by 73.8% at about 1 A/cm² and 56% at about 100 A/cm². These results are in general agreement with those of the reverse recovery time. The improvement in effective minority carrier lifetime as a result of introduction of universal contact is due to reduction in time constant τB in structure S-II. A plot of current ratio IhC/IB is shown in Fig. 7. It is clear from the figure that the hole current injected into the collector is significantly reduced in structure S-II, thereby implying less minority charge storage and improved reverse recovery.

As discussed earlier, the improvement in reverse recovery as a result incorporation of universal contact is accompanied with an increase in collector–emitter voltage, VCE(sat). Fig. 8 shows a comparison of the ON state for the two transistor structures of BVCEO of ~150 V ratings. The ON state voltage of S-II increases by 30–50 mV in comparison to BJT S-I. As discussed earlier, the increase in ON state voltage is due to reduced value of current gain in the reverse active mode. The current gain in the reverse active mode, for the two BJT structures are shown in Fig. 9. As can be seen, the current gain reduces from approximately 6 to 1.5 as a result of insertion of universal contact. Substitution of these values.
Eq. (21) predicts a difference of 28 mV in the ON state voltage of the two transistors in general agreement with the simulated values.

In order to estimate the impact of insertion of universal contact in transistors with high breakdown voltage, BJT with doping and other parameters suitable for operation of $\text{BVCBO} > 1000 \text{ V}$ was studied. Transistor structures S-I and S-II with description given in Table 2 and geometry with half emitter finger width of 100 $\mu\text{m}$ and base finger width of 150 $\mu\text{m}$ were simulated. Unlike their low voltage counterparts, the $I_c-V_{CE}$ curves for S-I and S-II high voltage transistor show some differences. Fig. 10 shows that there is no difference at large values of collector-emitter voltage but the collector currents for the two transistors begin to differ as the voltage gets smaller. The structure S-II is characterized by an early onset of quasi-saturation effect. This, as explained earlier, is due to reduced hole injection into the collector. Fig. 11 shows a comparison of reverse recovery time for the two structures. The improvement in reverse recovery for S-II is again noticeable though the magnitude is less being about 23.6% at 2 $\text{A/cm}^2$ and 20% at 40 $\text{A/cm}^2$. The improvements in effective minority carrier lifetimes are also similar.

At low collector current densities, the ON state voltage for S-II is only marginally higher due to reduced reverse current gain as explained for low voltage transistor above. However, as collector current density increases, the ON state voltage begins to increase at a lower collector current for structure S-II. This result is in

![Diagram](image)

**Fig. 10.** $I_c-V_{CE}$ characteristics of high voltage transistor S-I and S-II.
agreement with the predictions of the model Eq. (28) and (29) developed earlier for the dependence of voltage drop $V_U$ in quasi-saturation region. A plot of the ratio $V_U/J_C$ with respect to $I_{hc}/I_C$ in the region where collector–emitter voltage varies rapidly with collector current is shown in Fig. 12. The curves for both the transistors are similar in nature indicating that as the $I_{hc}/I_C$ ratio decreases, the ratio $V_U/J_C$ increases. However, the reduction of hole injection into the collector due to the incorporation of universal contact in S-II further reduces ratio $I_{hc}/I_C$. The reduced ratio $I_{hc}/I_C$ is responsible for larger unmodulated region in S-II and hence, higher $I_{hc}/I_C$ ratio as brought out in Fig. 12. Although Eq. (28) is a highly simplified description of the transistor in saturation mode of operation, it fits the simulated data quite well for both the transistor structures.

To summarize, the results of 2D numerical simulations are in general agreement with the predictions of the analytical model and indicate that significant improvement in reverse recovery is possible through incorporation of universal contact in the extrinsic base region. However, this improvement is obtained at the expense of increased ON state voltage especially for transistors designed for high voltage operation at relatively higher collector current densities.

4. Experimental results

4.1. Low voltage transistor

Conventional low voltage transistor S-I and the modified [3] transistor S-II were both fabricated adjacent to each other within the same wafer using the common double diffused epitaxial process. The photograph and details of the chip are given in Fig. 13(a). The doping, substrate thickness, junction depths, etc., are same as for simulated device shown in Fig. 4(b). The $I_C-V_{CE}$ characteristics of both S-I and S-II were identical and are shown in Fig. 13(b). A current gain ranging between 50 and 100 and identical breakdown voltages ranging between 100 and 155 V were measured for both S-I and S-II. The reverse recovery measurements were carried out using a resistive load and abrupt switching of the base voltage. The reverse recovery waveforms for S-I and S-II are shown Fig. 13(c) and (d) respectively. A reverse recovery time of $1 \mu s$ for S-I and $0.44 \mu s$ for S-II were obtained at a collector current of 20 mA. The 56% improvement in reverse recovery time is in fair agreement with simulation results considering the uncertainties due to factors such as collector recombination lifetime, Gummel charge under the extrinsic base, etc. used in simulation. The reverse recovery time for both S-I and S-II also decrease with increase in collector current density. For example, values of reverse recovery of 0.5 $\mu s$ at 10 mA and 0.38 $\mu s$ at 40 mA were measured for S-II.

Measurements of $V_{CE(sat)}$ were carried out for different collector currents. As can be seen from Fig. 13(e), the ON state voltage for S-II is higher as compared to S-I. As discussed earlier, at low currents, this is due to reduction in reverse current gain in S-II.

4.2. High voltage transistor

Conventional high voltage transistor S-I and the modified [3] transistor S-II were both fabricated in same batch using triple diffused process. The photograph and details of the chip are given in Fig. 14(a). The doping, substrate thickness, junction depths, etc. are same as for simulated device shown in Fig. 4(c). The $I_C-V_{CE}$ characteristics of structure are shown in Fig. 14(b). A current gain ranging between 15 and 25 and identical breakdown voltages $>1000$ were measured for S-I and S-II. The reverse recovery measurements were carried out
using a resistive load and abrupt switching of the base voltage. The reverse recovery waveforms for S-I and S-II are shown Fig. 14(c) and (d) respectively. A reverse recovery time of 10.4 $\mu$s for S-I and 8.4 $\mu$s for S-II were obtained at a forward collector current of 200 mA. The 23% improvement in reverse recovery time is in fair agreement with simulation results. The reverse recovery time for both S-I and S-II also decreased with increase in collector current density.

Measurements of $V_{CE(sat)}$ were carried out for different collector currents. As can be seen from Fig. 14(e), the on-state voltage for S-II is higher as compared to S-I. As discussed earlier, at low currents, this is due to reduction in reverse current gain in S-II. At high currents, it is due to the quasi-saturation as explained earlier.

No measurable difference in breakdown voltage and leakage current was observed in low and high voltage transistors S-I and S-II.

5. Conclusions

The use of “universal contact” for improving the reverse recovery of power bipolar transistor (BJT) was studied in detail using a combination of analytical model, numerical simulation and experimental work. It is shown
that use of universal contact allows redistribution of base current in saturation from collector region where recombination lifetime is high to extrinsic base region where effective recombination lifetime is low. The analytical model also predicts that the effective lifetime is inversely proportional to the current density. It is also shown through analysis that the efficacy of the universal contact in reducing the effective lifetime becomes less as the breakdown voltage of the transistor increases. The improvement in reverse recovery is accompanied by degradation of the ON state voltage. For low voltage transistor, the degradation is solely due to reduction in reverse current gain in reverse active mode while for high voltage transistor, the degradation is characterized by an early onset of quasi-saturation effect.

References

[2] Amemiya Y, Sugeta T, Mizushima Y. Novel low-loss and high speed diode utilizing an ‘ideal’ ohmic con-

