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Solid-State Electronics 47 (2003) 83–91
SOLID-STATE ELECTRONICS
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A study into the applicability of p^+n^+ (universal contact) to power semiconductor diodes for faster reverse recovery

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Received 26 April 2002; received in revised form 20 June 2002; accepted 28 June 2002

Abstract

The use of p^+n^+ universal contact for improving switching performance in diodes is studied in detail. A theoretical framework is described which shows that the incorporation of universal contact either at the end of the lightly doped region or in the injecting p or n regions of the diode can all be viewed as an attempt to reduce the effective minority carrier lifetime in the diode by redistributing minority carrier current from the lightly doped region of the diode where recombination lifetime is high to other regions of the diode where the presence of universal contact results in smaller recombination lifetime. It is shown that the incorporation of universal contact allows a new tradeoff between the effective recombination lifetime and the reverse blocking voltage determined by the proximity of universal contact to the lightly doped region of the diode. The impact of insertion of universal contact on reverse recovery is discussed as a function of current density and reverse blocking voltage.

Keywords: Power semiconductor diode; Semiconductor diode switches; Semiconductor device breakdown; Charge carrier lifetime; Current density; Charge carrier density

1. Introduction

Faster switching diodes are required in variety of applications including switching power supplies, TV deflection circuits, motor drives etc. The switching speed, characterized by reverse recovery time, depends on total minority carrier storage within the diode in ON state and the rate at which it is extracted when the device is switched to reverse bias. In conventional diode, the carrier storage is determined by the recombination lifetime of the lightly doped bulk region. High power diodes are made in high resistivity bulk material. The recombination lifetime in general increases as the doping decreases [1], so that as the doping is lowered to increase the breakdown voltage, its switching performance degrades. Adding suitable impurities like Au, Pt etc. or introducing radiation induced defects in the bulk of the device are important techniques commonly employed to decrease the recombination lifetime. But, this causes reverse leakage current and forward ON voltage to increase [2], not desirable in high power applications. Introduction of p^+n^+ universal contact [3] is yet another technique to reduce the reverse recovery time without increase in either the reverse leakage current or the forward ON voltage. This technique works well with diodes of low or moderate breakdown voltage, but degrades the reverse blocking voltage in diodes designed for higher voltage operation due to early onset of reach-through breakdown. A modified structure has been proposed [4], where the universal contact is incorporated inside the diffused region of the high voltage diode to avoid the early onset of reach-through breakdown. This also provided significant improvement in reverse recovery. In this paper we describe a theoretical framework within which the different ways of using universal contact for obtaining faster reverse recovery and its effect on other device parameters are dealt with in a unified manner.

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0038-1101/02/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0038-1101(02)00276-9

Nomenclature

D_n	average diffusion coefficient for electron
E_C	critical electric field for breakdown
f_L	safety factor for left diffused region to avoid punch-through breakdown
f_R	safety factor for right diffused region to avoid punch-through breakdown
J	total current density
I_L	current into the left p^+ diffused region
I_M	recombination current in the middle region
I_R	current into the right n^+ region
I	total current ($I_L + I_M + I_R$)
k	Boltzmann's constant
n	ideality factor for total current
n_i	intrinsic concentration
$N_{a(x)}$	acceptor diffused profile
η_L	ideality factor for current in left diffused region current
η_R	ideality factor for current in right diffused region
q	electron charge
Q	total charge stored in the diode
Q_L	minority charge stored in left p^+ diffused region
Q_M	minority charge stored in middle υ region
Q_R	minority charge stored in right n^+ region
Q_p	charge in p region (as defined in text)
ε_s	permittivity of silicon
τ_{eff}	effective lifetime
τ_M	high-level lifetime in middle region
τ_L	lifetime constant in left diffused region
τ_R	lifetime constant in right diffused region
T	300 °K
V_A	applied bias
V_L	built-in voltage at the pυ junction on left side
W_M	width of the middle υ region
x_1 and x_2	edges of depletion layer in p diffused region
x_{j1} and x_{j2}	metallurgical junction of n^+p and pυ
ξ_L	is the fraction of the area in which n^+ has been introduced in left p^+ diffused region
ξ_R	is the fraction of the area in which p^+ has been introduced in right n^+ diffused region

The paper has been organized in five sections. Section 1 refer to different ways of incorporation of universal contact and their advantages and drawbacks. It also refers to the scope of the paper. Section 2 deals with the theoretical development of charge control model for effective lifetime and its dependence on device parameters. Through simulation, it is shown that the effective lifetime is a good measure of reverse recovery. The simulation results have been included in this section for the clarity of the model developed. In Section 3, a new diode structure is proposed and a comparison of its reverse recovery with other diode structure is given. Section 4 includes analysis and simulation results of 'ON' state voltage. Section 5 gives the summary of the results.

2. Theory

In conventional diode structures shown in Fig. 1(a), henceforth referred to as structure S-I, most of the minority charge is stored in the lightly doped υ region. The holes that are injected into this region are confined by the reflecting υn^+ contact, which prevents their flow into the n^+ region. In the device proposed by [3], shown in Fig. 1 (b), henceforth referred to as structure S-II, an additional path for exit of holes from the lightly doped region has been provided through incorporation of the n^+p^+ universal contact. This result in substantial improvement in reverse recovery but as mentioned earlier, it also compromises the reverse blocking voltage in diodes designed for high breakdown voltage due to the early onset of reach-through breakdown. A modified diode henceforth referred to as structure S-III shown in Fig. 1(c), avoids the reach-through problem and also provides improvement in reverse recovery.

The improvement in switching delay obtained through incorporation of universal contact can be viewed from another angle, aside from the mechanism of providing easier path for the exit of minority carriers from the lightly doped region. The switching delay is closely related to the effective minority carrier lifetime in the device defined as

$$\tau_{eff} = \frac{Q}{I} \tag{1}$$

where Q is the total minority charge stored and I, is the total current flowing through the diode. Fig. 2 shows a comparison of the effective lifetime for a conventional diode structure S-I along with the total reverse recovery time as a function of current density. These results were obtained through 2D numerical simulations using the Silvaco device simulation package [5] for a diode of breakdown voltage of 1000 V. The description of the device is given in Fig. 3. 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. The reverse recovery time is defined as the total time for which the diode conducts in

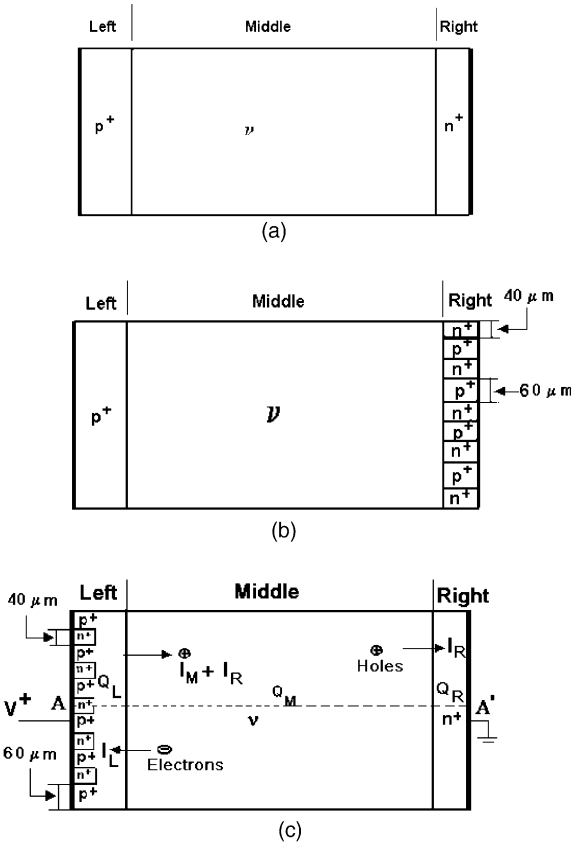

Fig. 1. (a) Conventional diode (S-I). (b) Diode structure (S-II) in which p^+n^+ universal contact has been introduced at the end of lightly diffused region. (c) Modified Diode (S-III) in which p^+n^+ universal contact has been introduced in left diffused region.

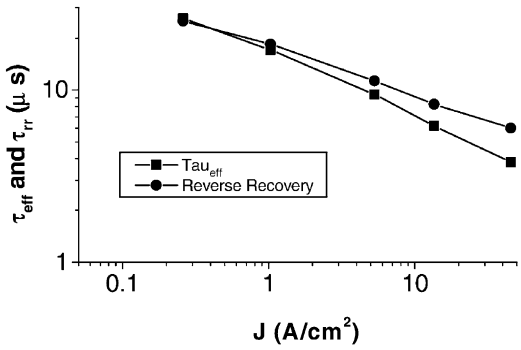

Fig. 2. Comparison of reverse recovery and effective lifetime (τ_{eff}) as a function of current density for high voltage diode (S-I).

the reverse direction and is the sum of storage and fall times. It can be seen from Fig. 2 that the effective minority carrier lifetime tracks the total reverse recovery time quite well. Although, reverse recovery waveform

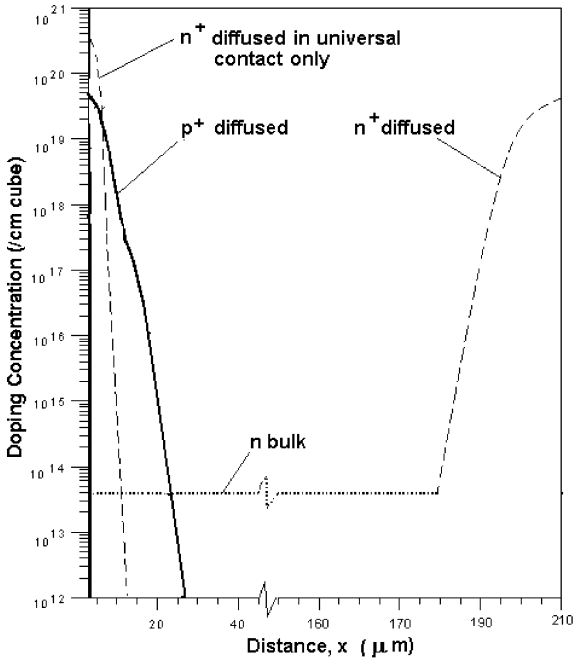

Fig. 3. Details of high voltage (~1000 V) conventional diode and diode incorporating universal contact.

can be quite complicated with several distinct regions such as storage time, fall time etc., for ease of analysis, the subsequent discussion will deal primarily with the effective lifetime.

The current I in Eq. (1) can be divided into three components [6], the minority electron current injected into the left region I_L, hole recombination current I_M, in the middle region and hole current I_R injected into the right region. Similarly, the minority charge Q, can be considered as having three components Q_L, Q_M and Q_R in the left, middle and right regions respectively. With these definitions, τ_{eff} may be re-written as

$$\tau_{eff} = \frac{\tau_M\left(1 + \frac{Q_L}{Q_M} + \frac{Q_R}{Q_M}\right)}{\left(1 + \frac{I_L}{I_M} + \frac{I_R}{I_M}\right)} \tag{2}$$

where $\tau_M = (Q_M/I_M)$ is high-level injection lifetime in the lightly doped middle region.

It is a fairly good assumption that the minority charges Q_L, Q_R in the p^+ and n^+ regions are much smaller than the minority charge in the Q_M in the middle region because the doping in left and right regions are much larger as compared to that in the middle region. However, the currents injected into the left and right regions are not negligible so that the Eq. (2) can be simplified to

$$\tau_{eff} = \frac{\tau_M}{\left(1 + \frac{I_L}{I_M} + \frac{I_R}{I_M}\right)} \tag{3}$$

Eq. (3) can be re-written in an alternative form as

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{L}}} + \frac{1}{\tau_{\text{M}}} + \frac{1}{\tau_{\text{R}}} \tag{4}$$

where $\tau_{\text{L}} = \tau_{\text{M}}(I_{\text{M}}/I_{\text{L}})$ and $\tau_{\text{R}} = \tau_{\text{M}}(I_{\text{M}}/I_{\text{R}})$.

Eq. (4) shows that the effective minority carrier lifetime in the diode is a function of three time constants only one of which is the recombination lifetime in the lightly doped middle region. The conventional approaches for improving reverse recovery, under the tacit assumption $\tau_{\text{eff}} \cong \tau_{\text{M}}$, have accordingly focussed attention on reducing this lifetime through incorporation of impurities such as Au, Pt etc. Eq. (4) however, suggests other alternative techniques for reducing the effective minority carrier lifetime by reducing other time constants such as τ_{L} or τ_{R}. The expressions for these time constants show that this would require an increase of either the I_{L}/I_M or the $I_{\text{R}}/I_{\text{M}}$ current ratios or both. The reason for this improvement is that while a thick, lightly doped middle region is well suited for the task of reverse blocking, it is unsuitable for carrying a substantial share of minority carrier current due to high recombination lifetime. On the other hand, the heavily doped n^+ and p^+ regions of the diodes are better suited to carry a larger fraction of minority carrier current because of lower recombination lifetimes in these regions. Accordingly, as indicated by Eq. (3), it makes sense to re-distribute minority carrier current away from the lightly doped middle region to other regions of the diode where lifetime is lower. This principle of re-distributing current away from regions of high recombination lifetime to regions of low recombination lifetime is well known and applied for example in BJTs, where sometimes a Schottky diode is connected across the collector–base junction so as to improve the transistor's switching performance. In this case a large fraction of the base current in saturation is diverted from the collector–base junction of the transistor, where minority carrier lifetime is high, to Schottky diode, which is characterized by negligible minority carrier storage. The use of universal contact provides a mechanism for implementing this principle within PIN diodes as explained in detail below.

Let us consider how the ratio $I_{\text{L}}/I_{\text{M}}$ can be increased so as to reduce the effective recombination lifetime. The current I_{L} results from injection of electrons into the p diffused left region. These electrons are normally reflected back by the sharply increasing p-type doping profile, thus limiting the minority carrier current I_{L} to a small value. However, if a "universal contact" is incorporated in the diffused region, the minority carrier current I_{L} can be significantly increased. This contact should however be inserted so that there is no reach-through breakdown prior to avalanche breakdown when the diode is in the reverse blocking state. This can be done by restricting the depth of n^+ diffusion to less than the extent of the depletion layer at the breakdown voltage. This structure is expected to result in improvement in switching performance but without any decrease in reverse breakdown voltage.

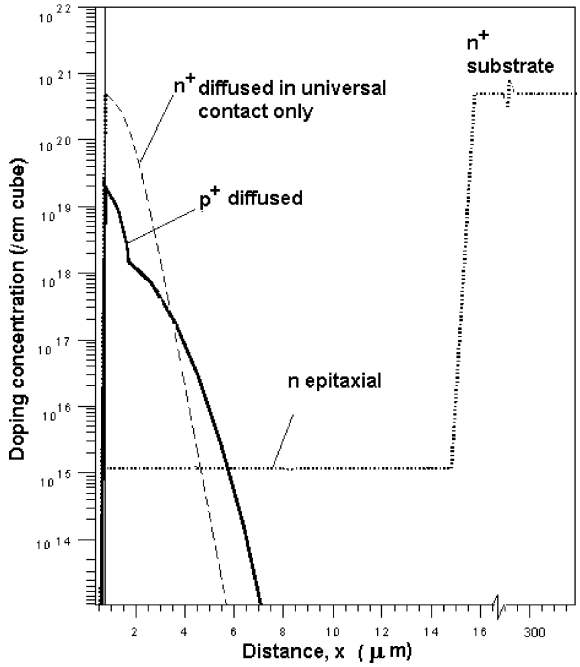

Fig. 4. Details of low voltage (~150) conventional diode and diode incorporating universal contact.

To verify the above concept, the diodes S-I and S-III were studied through 2D numerical simulations. The details of the diode structures of voltage of 150 V are shown in Fig. 4. Fig. 5 shows a comparison of the effective lifetime obtained for the diodes S-I and S-III. The effective lifetime decreases from 849 to 194 ns, a reduction of 77% at 1 A/cm^2 and from 88 to 28 ns a reduction of 68% at about 110 A/cm^2. The improvement in effective lifetime obtained was found to be similar to the improvement observed in reverse recovery indicating that effective minority carrier lifetime is a good and simple measure of the switching performance of the diode. Fig. 6 shows a comparison of effective lifetime of the two structures designed for reverse blocking voltage of around 1000 V. In these high voltage diodes, τ_{eff} decreases from 26 to 15.4 μs, a reduction of 41% at 1 A/cm^2 and from 3.8 to 2.3 μs, a reduction of 39% at about 50 A/cm^2. These results can be explained in terms of changes in the current ratio $I_{\text{L}}/I_{\text{M}}$. Figs. 7 and 8 show a comparison of the ratio $I_{\text{L}}/I_{\text{M}}$ for the low and high voltage diodes respectively. The reduction of reverse recovery time by 77% for the low voltage case can be largely attributed to an increase of the ratio $I_{\text{L}}/I_{\text{M}}$, from 5 to 38.6. Similarly, the results for high voltage diode can be attributed to improvement in the $I_{\text{L}}/I_{\text{M}}$ ratio.

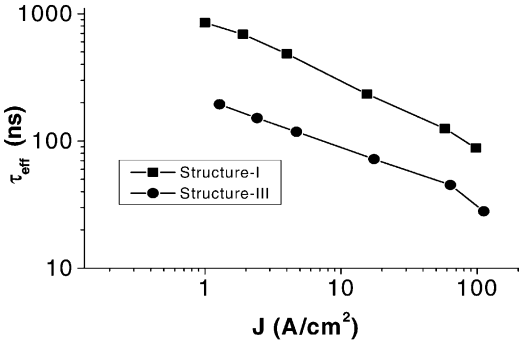

Fig. 5. τ_{eff} vs J for low voltage diodes (S-I and -III).

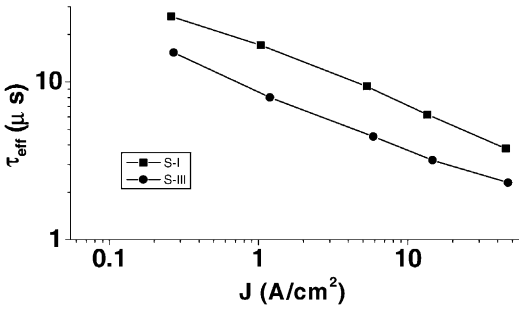

Fig. 6. τ_{eff} vs J for high voltage diode (S-I and -III).

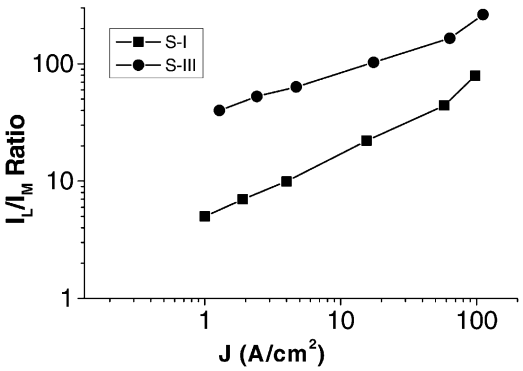

Fig. 7. I_L/I_M ratio for low voltage diodes (S-I and -III).

During reverse recovery, the reverse current consisting of holes flows only through the p^+ part of the universal contact. This results in lateral current flow and voltage drop under the n^+ regions of the universal contact which may result in turn on of the parasitic n^+pvn^+ transistor [7]. However, it was found through simulation that even for n^+:p^+ :: 60 μm:40 μm, the voltage difference under p^+ and n^+ is only a few mV and turn-on of the parasitic transistor is not observed.

Since the current ratio I_L/I_M is the most important factor affecting the minority carrier lifetime, let us look at some of the important factors that influence this ratio.

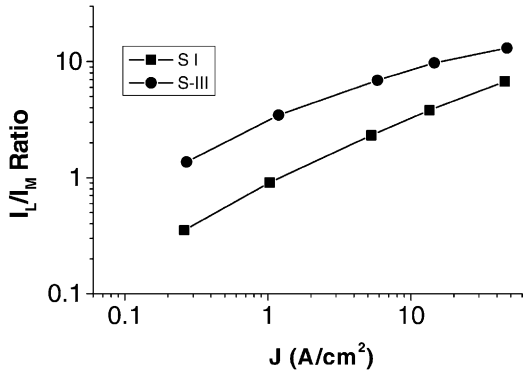

Fig. 8. I_L/I_M ratio for high voltage diodes (S-I and -III).

The current injected into the left region, I_L can be divided into two components: a component, I_{L1} flowing under n^+ and other component, I_{L2} under p^+. Since $I_{L1} \gg I_{L2}$, $I_L \approx I_{L1}$. Fig. 9 shows a one-dimensional (1D) view of the device in the region where n^+ diffusion in p diffused region has been made. x_{j1}, x_{j2} and x_{j3} are the metallurgical junctions of front n^+p "universal contact", pυ diode and back υn^+ contact. x_1 and x_2 are the depletion edges of n^+p and pυ junctions inside the p diffused region. Under steady forward bias conditions, the current density I_L due to electron flow in the left p diffused region can be written [8] as

$$I_L = \frac{q^2 n_i^2 D_n \exp\left(\frac{qV_L}{kT}\right)}{Q_p} \xi_L A \tag{5}$$

where A is the area of the diode and ξ_L is the fraction of the area in which n^+ has been introduced in left diffused region. Defining a factor $\eta_L = (V_A/V_L)$, where V_A is the applied voltage, Eq. (5) may be written as

$$I_L = q^2 n_i^2 D_n A \frac{\exp\left(\frac{qV_A}{\eta_L kT}\right)}{Q_p} \xi_L \tag{6}$$

For simplicity, we assume that when junction is forward biased $x_2 = x_{j2}$ and low level injection conditions prevail

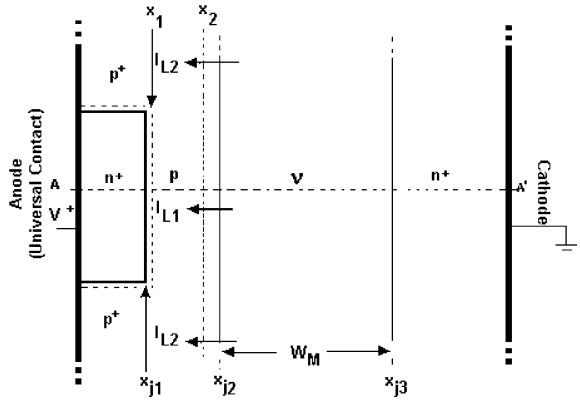

Fig. 9. 1D view under n^+ (cross-section at A–A′) of Fig. 1(c).

so that $Q_p = q\int_{x_1}^{x_{j2}} N_a(x)\,dx$. To avoid punch-through prior to onset of breakdown, we require that at breakdown $(x_{j2} - x_1) > 0$. Taking E_C as the critical field, we obtain the condition

$$\frac{q}{\varepsilon_s}\int_{x_1}^{x_{j2}} N_a\,dx > E_C \quad \text{or } Q_p > \varepsilon_s E_C \tag{7}$$

Defining $f_L = (Q_p/\varepsilon_s E_C)$, allows Eq. (5) to be re-written as

$$I_L = q^2 n_i^2 D_n A \frac{\exp\left(\frac{qV_A}{\eta_L kT}\right)}{f_L \varepsilon_s E_C}\xi_L \tag{8}$$

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

The middle region current, I_M is the minority carrier current and can be modeled as recombination current [9], which may be written as

$$I_M = qn_i A\frac{W_M}{\tau_M}\exp\left(\frac{qV_A}{\eta_M kT}\right) \tag{9}$$

where η_M is the ideality factor of the current, I_M. The ratio I_L/I_M can now be obtained using Eqs. (8) and (9) as

$$\frac{I_L}{I_M} = qn_i D_n \frac{\tau_M}{W_M}\frac{\exp\left(\frac{qV_A}{kT}\left(\frac{1}{\eta_L} - \frac{1}{\eta_M}\right)\right)}{f_L \varepsilon_s E_C}\xi_L \tag{10}$$

The total current density J of the diode may be written in terms of its ideality factor n as

$$J = J_0 \exp\left(\frac{qV_A}{nkT}\right) \tag{11}$$

Eq. (11) can be used to re-write Eq. (10) as

$$\frac{I_L}{I_M} = C_L \frac{\tau_M}{W_M}\frac{J^{\alpha_L}}{f_L}\xi_L \tag{12}$$

where $\alpha_L = n((\eta_M - \eta_L)/\eta_M\eta_L)$ and constant factor, $C_L = (qn_i D_n/\varepsilon_s E_C J_0^{\alpha_L})$.

Substitution of Eq. (12) in Eq. (3) and neglecting the ratio I_R/I_M that is smaller than the ratio I_L/I_M, we obtain

$$\frac{1}{\tau_{eff}} \cong \frac{1}{\tau_M} + \frac{1}{\tau_L} \tag{13}$$

where $\tau_L^{-1} = C_L(J^{\alpha_L}/f_L W_M)\xi_L$.

Eq. (13) predicts that the effective lifetime will decrease with increase in current density. This is due to the different ideality factors of the current injected into the middle and the left regions of the diode. The minority hole current in the middle region increases as $\exp(qV_A/2kT)$ due to high level injection in the middle region, while the current injected into the left region increases as $\exp(qV_A/kT)$ due to low level injection condition, causing the ratio I_L/I_M to increase with increase in bias or time constant τ_L to decrease with increase in current density. Eq. (13) also shows that the impact of insertion of universal contact on effective lifetime will decrease as the breakdown voltage of the diode increases. This is because increase of breakdown voltage requires increase of the thickness W_M of the lightly doped middle region, which increases the time constant τ_L. Thus, like the conventional PIN diode, in this case also, there is a tradeoff between the reverse recovery and the reverse blocking voltage.

Instead of the left p^+ region, the universal contact can also be inserted in the right n^+ region. For this case, an expression similar to Eq. (13) can be written

$$\frac{1}{\tau_{eff}} \cong \frac{1}{\tau_M} + \frac{1}{\tau_R} \tag{14}$$

where $\tau_R^{-1} = C_R(J^{\alpha_R}/f_R W_M)\xi_R$.

Both Eq. (13) as well as Eq. (14) show that a decrease in safety factor can result in improvement in the effective lifetime. In fact, f_R may be made even less than unity by inserting the universal contact deeper into the n^+ region. In this case the reverse blocking voltage would be compromised due to onset of reach-through prior to avalanche breakdown. This illustrates that the reverse blocking characteristics can be traded with the switching characteristics in a new manner determined by the proximity of the universal contact to the edge of the lightly doped region. This is exactly what is done in the structure S-II proposed by [3] where the universal contact is inserted in the right n^+ region of the diode such that it is contiguous with the middle region. Although Eq. (14) ceases to hold when f_R becomes zero, we expect that a large decrease in effective lifetime would result at the expense of a drop in the reverse blocking voltage especially in diodes designed for high voltage operation. This is illustrated in Fig. 10 where the structures S-I and S-II are compared. As can be seen, the effective lifetime is significantly reduced in diode S-II in comparison to conventional diode S-I. Fig. 11 shows a comparison of the ratio I_R/I_M for the two structures, S-I and S-II. The increase in this current ratio for S-II completely accounts for its better performance. The simulated reverse characteristics of diode S-I and S-II are shown in Fig. 12. It can be seen that the diode S-II suffers from premature breakdown due to reach-through between the two p^+ regions, one on the left and the other on the right side. The onset of this p^+np^+ reach-through in S-II limits the reverse blocking voltage to less than half the breakdown voltage of the conventional diode S-I. This reach-through phenomenon is either absent or less severe in low voltage diodes because the doping in the middle region is relatively high and as a result, the depletion layer on application of reverse bias does not reach the p^+ region even at breakdown voltage.

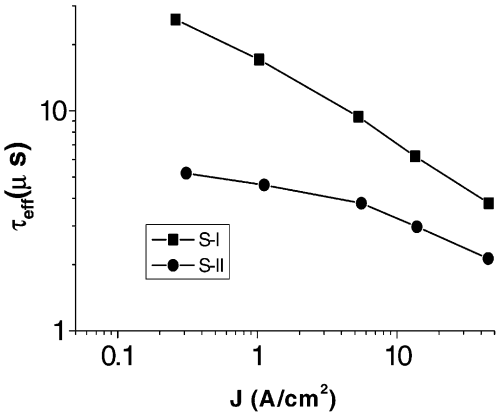

Fig. 10. τ_{eff} vs J of high voltage diode (S-I and -II).

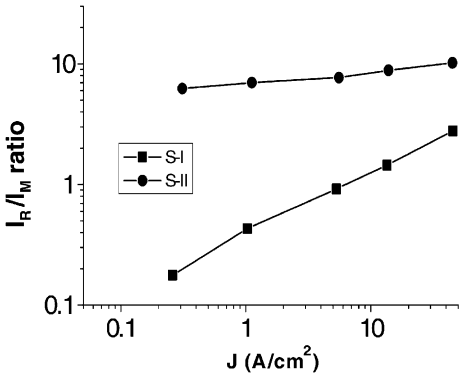

Fig. 11. I_R/I_M for high voltage diode (S-I and -II).

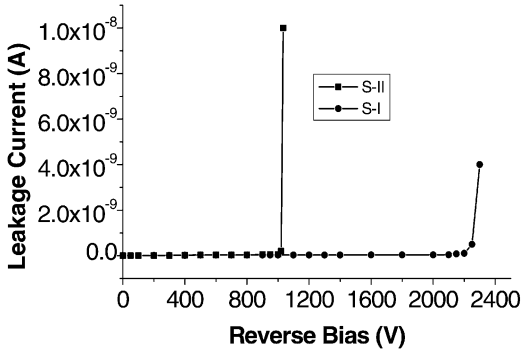

Fig. 12. Simulated breakdown voltage of diodes (S-I and -II).

3. A proposed diode structure

The improvement in effective minority carrier lifetime would be maximum when "universal contact" is incorporated in both the left p^+ and the right n^+ regions as illustrated in Fig. 13, henceforth referred to as diode

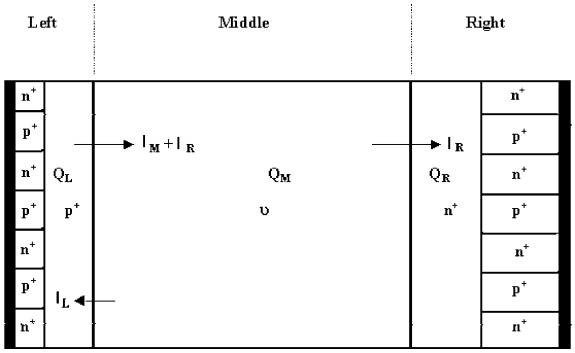

Fig. 13. Structure of proposed diode (S-IV).

S-IV. By keeping the safety factors larger than unity, the new structure is expected to give significant improvement in effective lifetime without compromising the reverse blocking voltage. A comparison of effective lifetimes for the structures S-I, -II, -III and -IV is shown in Fig. 14 for a diode designed for reverse blocking voltage of 1000 V. As expected, the new structure S-IV shows better effective lifetime than that of diode S-I and diode S-III. It also compares well with diode S-II, particularly at higher current density. Figs. 15 and 16 show a comparison of current ratios I_L/I_M and I_R/I_M for the different diodes S-I to -IV. The improvements in reverse recovery are 60% and 66% at low and high current densities respectively in the proposed structure with respect to normal structure. The corresponding values of reverse recovery improvement in diode S-II are 74% and 40%. The better performance of the new structure S-IV can be attributed to improved values for both I_L/I_M and I_R/I_M ratios in the device. It was also observed during simulation that there was no decrease in breakdown voltage due to reach-through in diode S-IV in comparison to conventional diode S-I.

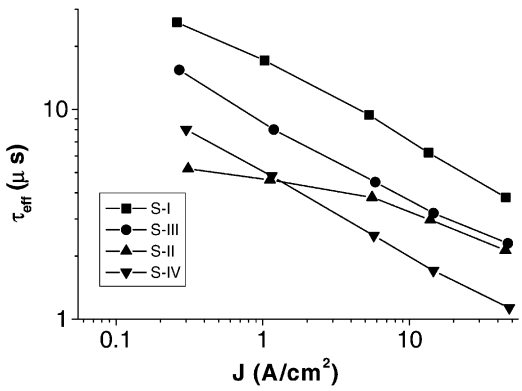

Fig. 14. A comparison of τ_{eff} vs J of diodes (S-I, -II, -III and -IV).

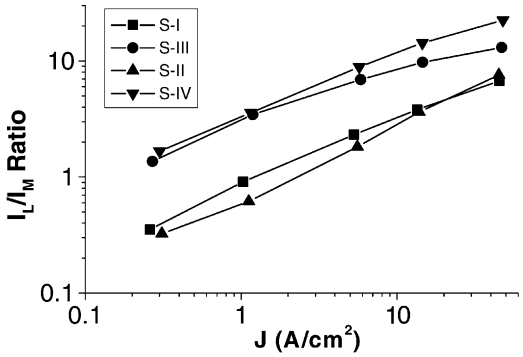

Fig. 15. I_L/I_M vs J of diodes (S-I, -II, -III and -IV).

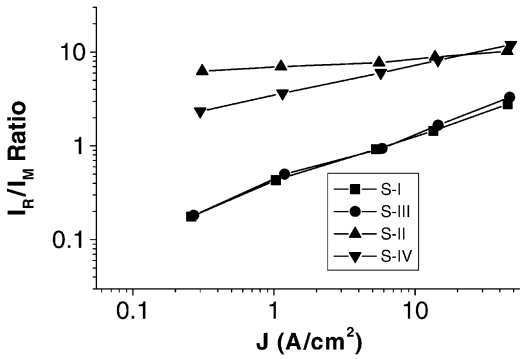

Fig. 16. I_R/I_M vs J of diodes (S-I, -II, -III and -IV).

4. Forward 'ON' voltage

The insertion of universal contact besides resulting in improvement in reverse recovery performance is also accompanied with an improvement in forward ON voltage. This can be explained by noting that the total current flowing through the device can be expressed as

$$I = I_L + I_M + I_R = I_M\left(1 + \frac{I_L}{I_M} + \frac{I_R}{I_M}\right) \tag{15}$$

Eq. (15) implies that an increase in I_L/I_M or the I_R/I_M ratio would result in an overall increase in the total current flowing through the device for the same applied voltage or a decrease in forward ON voltage for the same current. A comparison of the simulated forward 'ON' voltage of high breakdown voltage diodes is shown in Fig. 17. The voltage is the difference between the hole quasi-Fermi voltage and electron quasi-Fermi voltage in the forward 'ON' state of different simulated diode structures at different current densities. The forward ON voltage of the diode S-II is the least amongst all the diodes at less than about 5 A/cm^2. Above, 5 A/cm^2, the proposed diode is having the least forward ON voltage amongst all the four simulated diode structures.

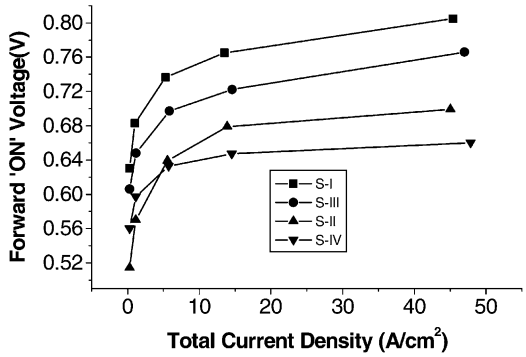

Fig. 17. Forward 'ON' voltage of diodes (S-I, -II, -III and -IV).

In addition to incorporation of universal contact in the end regions, use of hetero-structures can also be potentially used to further improve the effective lifetime. By using a wide band-gap semiconductor in the middle region and suitable narrow band-gap semiconductors in the end regions, the current ratios I_L/I_M and I_R/I_M could possibly be considerably increased leading to very low effective minority carrier lifetimes in the device.

5. Summary

A new theoretical framework for describing the improvement in the switching performance of PIN diodes offered by incorporation of n^+p^+ "universal contact" has been proposed. It is shown that besides the minority carrier lifetime in the lightly doped region, other time constants determined by fraction of current injected into the p^+ and n^+ regions of the diode also provide a mechanism for reducing the effective minority carrier lifetime in the diode. It is also shown that the incorporation of universal contact offers new ways of trading reverse blocking voltage against the reverse recovery time. A diode structure incorporating universal contact in both left (p^+) and right (n^+) regions of the diode is shown to result in maximum improvement in the diode's switching performance without compromising the breakdown voltage.

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