Physical effect on transition from blocking to conducting state of barrier-type thyristor

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Abstract: The transition of the barrier-type thyristor (BTH) from blocking to conducting-state occurs between two entirely contrary physical states with great disparity in nature. The physical effects and mechanisms of the transition are studied in depth. The features of the transition snapback point are analyzed in detail. The transition snapback point has duality and is just the position where the barrier is flattened. It has a significant influence on the capture cross-section of the hole and high-level hole lifetime, resulting in the device entering into deep base conductance modulation. The physical nature of the negative differential resistance segment I–V characteristics is studied. It is testified by using experimental data that the deep conductance modulation is the basic feature and the linchpin of the transition process. The conditions and physical mechanisms of conductance modulation are investigated. The related physical subjects, including the flattening of the channel barrier, the buildup of the double injection, the formation of the plasma, the realization of the high-level injection, the elimination of the gate junction depletion region, the deep conductance modulation, and the increase in the hole's lifetime are all discussed in this paper.

Key words: barrier-type thyristor; negative differential resistance; physical effect; conductance modulation
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1. Introduction

The most prominent strongpoint of the barrier-type thyristor (BTH) is its complete switch function, which has the capability of turning on or off optionally. Therefore，it has wide applications in power switching fields. One particular feature of the BTH is that it can build up a barrier for a blocking function, i.e., bearing high voltage and blocking current flow. On the other hand, excellent conducting capability is essential to the BTH, which means that it also needs to conduct very large currents with a small voltage drop that also represents another nature or active state of the BTH. Although the two natures or states have their own disparity and even contrasting requirements, they must be exhibited on one device that hence forms the unique characteristics of the BTH. The linchpin of the blocking function is that high enough channel barriers must be built up. The height of the barrier is $e\Phi_{\min}$ ($\Phi_{\min} < 0$). However, the BTH can never have the barrier on the current passage from anode A to cathode K in the conducting state. The only way to satisfy the different requirements for these two functions is that the barrier can be built up or flattened at any time. The authors have named this process 'flatten the barrier'. That is to say, the BTH works not only in two stable states but also in a dynamic process, i.e., the transition between two stable states. It can be imagined that it is not easy to realize the transition between two states, which have differences in features and function mechanisms. This is a consequence of multi physical effects by all means. The study on the transition is not only an important but also a complicated subject. However, it is regretful that few of papers have been devoted to the physics and mechanisms of the transition behaviors of BTHs up to now[1, 2]. Most of them have been concerned with the device fabrication and application fields[3−6]. Therefore, the transition behaviors of BTHs from blocking to conducting states are discussed (including several new theories) and delicate analyses on the basis of the fabrication practices of BTHs in this paper. Some specious or ambiguous parlances are clarified too.

2. Transition from blocking state to conducting state

Since the BTH used here is a kind of 'normally off' device, this is taken into account during the structural design and fabrication of the device. The typical I–V characteristics of the BTH are given in Fig. 1. The forward blocking-state characteristic with small current is shown in Fig. 1(a). This exhibits triode-like characteristics as a static induction transistor (SIT). Figure 1(b) is the negative differential resistance (NDR) characteristic of the transition from forward blocking state to conducting state, but has not yet been realized. Figure 1(c) is characteristic when the BTH is just in the process of NDR transition towards the conducting state. Figure 1(d) shows the characteristic of the forward conducting state that is characterized by a large current and a very low conducting-state voltage drop.

Figure 2 shows a diagrammatic sketch of the BTH's transition characteristics. The curve BF represents the transition process. This begins from point B and ends at point F. The state represented by F is the conducting state that is characterized by a low voltage drop and a large current. The nature and features of the turning point B are discussed below.

2.1. Features of turning point

The features of the turning point are as follows:

(1) The line BF represents the turn-on line of the device.

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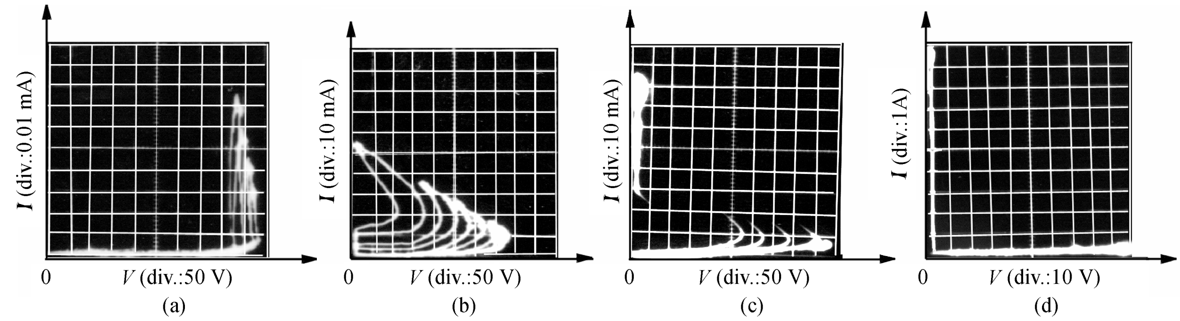

Fig. 1. Typical I–V characteristics of the BTH. (a) Forward blocking-state triode-like characteristics with small current. (b) Quasi-blocking state with medium and larger current, accompanied by the NDR transition from the blocking state to the conducting state, but not yet realized. (c) Process of the NDR transition towards the conducting state. (d) Forward conducting state that is characterized by a large current and a very low conducting-state voltage drop.

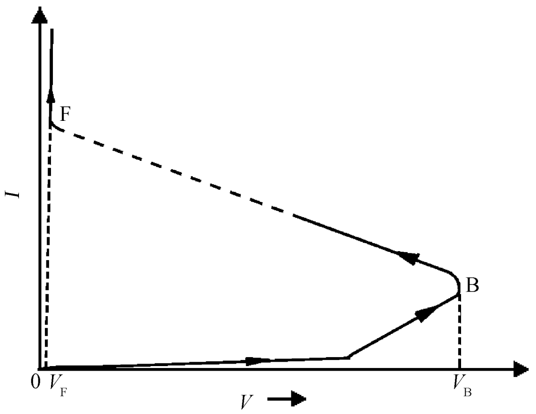

Fig. 2. Diagrammatic sketch of the NDR transition from blocking to conducting state of the BTH.

The process before point B is a preparatory stage. The BTH enters a critical and dynamic state when it reaches point B and at this time all parameters change rapidly. Point B has the feature of duality since it is the start of the conduction that already has the basic features of the conducting state. Although it has not yet turned on completely as point F, points B and F have only the degree difference. On the other hand, point B is developed from the blocking state, so it still retains certain basic features of the blocking state. Therefore, point B is neither a turn-on nor a turn-off point.

(2) When the device is entering the conducting state, the barrier should not exit on the current passage. Thus it indicates that point B is the position where the barrier is flattened[7], i.e.,

$$\Phi_{\min}(x_{\min}, 0) = \Phi_{\min}(0, 0) \approx 0. \tag{1}$$

The voltage drop on device $V_{\mathrm{AK}}(t)$ is the barrier flatten voltage $V_{\mathrm{A,f}}(t)$, i.e.,

$$V_{\mathrm{AK}}(t) = V_{\mathrm{A,f}}(t). \tag{2}$$

Thus the corresponding current is

$$I_{\mathrm{A,f}}(t) = \frac{V_{\mathrm{A}} - V_{\mathrm{A,f}}(t)}{R_{\mathrm{L}}}. \tag{3}$$

The device will be turned on apace ($t_{\mathrm{on}} \approx (2\text{–}3) \times 10^{-7}$ s in experimental results). $V_{\mathrm{AK}}(t)$ will decline to V_{F}, which is represented by point F. V_{F} is the sum of the two forward junctions' voltage drop.

$V_{\mathrm{F}} = V_{\mathrm{jn^+}n^-} + V_{\mathrm{jp^+}n^-} \approx 0.32 + 0.7 \approx 1$ V. Accordingly, the current will be increased tending to a maximum.

$$I_{\mathrm{A}} \to \frac{V_{\mathrm{A}}}{R_{\mathrm{L}}}. \tag{4}$$

(3) The current is a unipolar electron current before point B, $j_{\mathrm{A}} \approx j_{\mathrm{n}}$. From point B, the BTH enters into the bipolar state. The electrons and holes are injected from the anode and cathode, respectively, resulting in the formation of a high density of plasma. Electrons and holes have common bipolar parameters and obey the same equations. The processing of these issues should consider the 'bipolar effect'. Thus, B is also the transition point from the unipolar to the bipolar state.

(4) Point B depicts that the device is entering into the high-level injection state. All of the high-level effects act especially under the situation when injected holes fill the recombination centers. This has a significant influence on the capture cross-section of hole σ_{p} and high-level hole lifetime τ_{ph}, resulting in the BTH entering into deep base conductance modulation. Thus, B is the turning point from low-level to high-level injection as well.

(5) From point B, the I–V characteristic starts the segment of negative differential resistance characteristics, $\mathrm{d}V/\mathrm{d}I < 0$, ($\mathrm{d}V < 0$, $\mathrm{d}I > 0$), namely, V_{AK} declines with the increase in current instead of rising until it reaches $V_{\mathrm{AK}} = V_{\mathrm{F}}$ at point F. This just manifests the increase in τ_{ph} and deep base conductance modulation.

(6) From point B the current changes from barrier-controlled current to double injection current that has an unequitime lifetime[8]. The space charge recombination and neutralizing effect at the base lead to a dramatic current increase. The I–V characteristic exhibits the square-law relationship again at the end of the negative resistance segment as follows,

$$j \approx e\tau_{\mathrm{p,h}}\mu_{\mathrm{n}}\mu_{\mathrm{p}}N_{\mathrm{t}}\frac{V_{\mathrm{F}}^2}{W_{\mathrm{n}}^3}, \tag{5}$$

where V_{F} corresponds to the low-voltage end, which is the transition voltage from negative resistance to square-law segment. When the injection rate is larger than the recombination rate at last, the I–V characteristic becomes a cubic-law relationship[9].

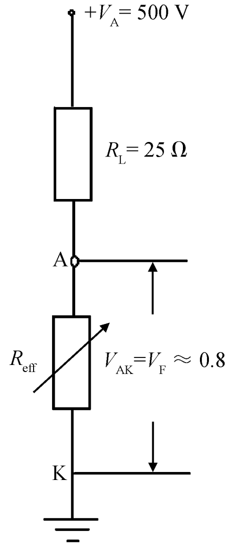

Fig. 3. Effective resistance R_{eff} of the BTH.

2.2. Deep conductance modulation

The negative resistance characteristic is the most important transit characteristic, which is only represented by the BF segment in the whole I–V characteristic of the BTH. This indicates that the negative resistance segment is an inevitable process for a device turning to the conducting state. Otherwise it is impossible to realize the transition between the two stable states. The conductance modulation is the basic feature and the linchpin of the transition process. It is unavoidable that the effective resistance of the BTH itself varies from high resistance in the blocking state to extremely low resistance (≈ 0). For the sake of making out its extreme importance, the value estimation by using our experimental data is necessary. Figure 3 shows the effective resistance R_{eff} of the BTH that can reflect the huge change in turn-on or turn-off state effectively as a variable resistance. For the BTH made by us, the barrier operates in the blocking state. Supposing $\Phi_{min} = -0.83$ V, $j_A = 1.4 \times 10^{-8}$ A, and the active region area of the device $A_K = 2.61 \times 10^{-2}$ cm^2, thus the current $I_A = 3.65 \times 10^{-10}$ A and $R_{eff} = 1.4 \times 10^{12}$ Ω. This is an excellent blocking state. If we lower the requirement for the blocking state before nearing point B shown in Fig. 2, setting $\Phi_{min} = -0.56$ V, then $j_A = 4.4 \times 10^{-4}$ A, $I_A = 1.1 \times 10^{-5}$ A. Even in this case, the R_{eff} can be 4.55 $\times 10^7$ Ω. When in the conducting state (Fig. 3), $V_{AK} = V_F \approx 0.8$ V, the corresponding R_{eff} is 4×10^{-2} Ω, which is only 8.8×10^{-10} times R_{eff} in the blocking state. It is obvious that the decrease is very dramatic. The resistivity of the original n-Si $\rho = 100$ Ω·cm, which corresponds to the channel impurity $N_D^- \approx n_0 = 5 \times 10^{13}$ cm^{-3}. When in the high-level injection, supposing $n \approx p \geqslant 10^{18}$ cm^{-3}, and the bipolar mobility $\mu_a = 200$ cm^2/(V·s), then the effective resistivity is 0.0156 Ω·cm, which is only 1.56×10^{-4} times the original resistivity. This also shows that the decrease in base resistivity is very large simultaneously. Therefore, it has done the preparation for deep conductance modulation and large current conduction.

2.3. Physical effects related to transition

The negative differential resistance characteristic of the BTH implies the profound change of device action mechanism. The reason for the BTH having the ability to change between two totally different states is just what we need to study here aiming at the physical nature of device transition.

2.3.1. Flattening the barrier is prerequisite

It is not allowed that there is barrier on the current passage. We change the field contrastive relationship between the forward and reverse field in the channel by enhancing the anode field E_A until the barrier is flattened. The quantitative dependence on the gate voltage for building up the barrier $V_{G,B}$, the height of the barrier Φ_{min} and the flatten voltage of the barrier $V_{A,f}$ are given by the authors in Ref. [7] for the first time.

2.3.2. Establishing the double injection effect

The double injection effect is a kind of physical phenomenon that generally exists in power devices. It is impossible to realize deep conductance modulation without the double injection effect, i.e., without holes taking part in the current's conducting. Hence the BTH can never realize the negative resistance transition and large current transfer without it. The key for establishing the double injection effect is that the injected minority carriers can pass through the drifting region reaching to the cathode. This means that the transit time for the holes from anode to cathode t_p should not be longer than its lifetime τ_p, i.e.,

$$t_p = \frac{W_n^2}{\mu_p V_B} \leqslant \tau_p, \tag{6}$$

where μ_p is the mobility of hole and V_B is the anode voltage that corresponds to turning point B. This shows that with increasing V_A the anode field E_A is enhanced continuously till go through the whole device and flattened the channel barrier. Therefore holes can transit to the cathode and the double injection is established. When the injection-level is high enough, the plasma with a high and equal density of holes and electrons is formed and fills the base. In other words, the plasma has been injected into the base region. Then we get

$$n(x) = p(x), \tag{7}$$

$$\frac{dn(x)}{dx} = \frac{dp(x)}{dx}. \tag{8}$$

Thus the carrier's transfer can be expressed by the same equations. Accordingly, the related parameters are all bipolar parameters, e.g., bipolar diffusion coefficient D_a, bipolar mobility μ_a and bipolar lifetime τ_a, which are not only related to the corresponding parameters under low-level injection condition but also to functions of the injection level[9]. Then the current becomes

$$j_n = j_p = \frac{1}{2} j. \tag{9}$$

It is necessary to give the physical meaning of Eq. (9) here. It is impossible to conduct large current only depend on one kind of carrier, whereas the formation of plasma can conduct large current by two kinds of carriers that exactly satisfy the requirement of large current conduction. For high concentration plasma, the electron diffusion current equals the hole diffusion current with opposite signs. They counteract each other, resulting in the total diffusion current becoming zero. The current through the base region is only the drifting current of the carriers. The electron drifting current equals the hole drifting current, which is half of the total current, i.e.,

$$j_n = j_p = 2e\mu n(x)E(x) = 2e\mu p(x)E(x). \quad (10)$$

Thus the electrical field distribution can be obtained as

$$E(x) = \frac{j}{2e\mu p(x)}. \quad (11)$$

Therefore, as long as we get $n(x) = p(x)$, the electrical field distribution $E(x)$ and hence the body voltage drop can be obtained[9].

2.3.3. High-level carrier injection and elimination of gate junction depletion region

The barrier is similar to a 'sluice gate'. Once the 'sluice gate' opens, electrons and holes enter into the n^- base region, including the channel and drifting region, as majority and minority carriers from the cathode and anode under high-level injection, respectively. Two kinds of carriers both perform their own important effect in the conduction transit processing.

The functions of injected electrons are as follows:

(1) Charge the reverse-biased gate junction depletion region that leads to the depletion region contracting rapidly towards the gate body until it disappears. Then the n^- base region is neutralized and enters conductance modulation.

(2) Supply electrons to maintain the reverse biasing function of the gate junction being voided.

(3) Neutralize the minority carrier injected from the anode and converge them making its concentration increase continuously and maintaining steady distribution finally, i.e., $n(x) = p(x)$, $\frac{dp(x)}{dx} = \frac{dn(x)}{dx}$.

(4) Form the e–h plasma together with holes to accomplish bipolar current conduction, $j = j_n + j_p$, and form the base deep conductance modulation.

(5) Replenish electrons that have been recombined at the base region and maintain the dynamic balance of the recombination.

The functions of injected holes are as follows:

(1) Form the plasma together with majority carriers to accomplish bipolar current conduction in order to realize the base deep conductance modulation.

(2) Neutralize electrons and converge them to maintain steady distribution $p(x)$.

(3) Replenish the holes that recombined at the base region and maintain the dynamic balance of the recombination.

(4) Distribute the current for the collection (gate) region and charge gate junction leading to it cannot have the reverse biasing function.

(5) Maintain the high-level injection state and the acceptor-like type recombination center being filled up with holes.

2.3.4. Increase of hole's lifetime

(1) Electrons occupy the recombination center energy level E_t of the lightly doped n-Si base region with the tendency to capture holes even under the low-level injection state. Generally, only the deep acceptor-state recombination centers are taken into account for n-Si. (For p-Si, the donator-state recombination centers are considered instead). In this paper, we only consider the acceptor-like type of single recombination energy level and treat the variation of the lifetime of τ_p approximately by using single energy level recombination theory. There are two electrical states in this energy state, i.e., electronegative and neutral states.

(2) Here, $n_0 = N_D^- = 5\times10^{13}$ cm^{-3}, then $p_0 = 4.5\times10^6$ cm^{-3}, $N_t = 1\times10^{11}$ cm^{-3}. E_t is far under the Fermi energy level E_{Fn}. The shallow donor concentration of n-Si is higher than that of the recombination centers, $n_0/N_t = 5\times10^2$. All recombination centers are filled with electrons and hence exhibit negative electric centers under a thermal equilibration state. Setting the capture cross-section of the empty neutral center for electrons in the conduction band is $\sigma_n(\sigma_n^0)$; the capture cross-section of the negative electric centers for holes in the valence band is $\sigma_p(\sigma_p^-)$. When in the low-level injection there is no possibility for recombination centers to capture electrons because they are already filled with electrons, namely, σ_n^0 is extremely small. Therefore the lifetime of electron τ_n^0 is very long and can even be considered as approaching infinity. In contrast, holes in the valence band are far less than the negative electric centers, $N_t/p_0 = 2.2\times10^4$, all negative electric centers are ready trending to capture holes, i.e., σ_p is quite large which means the lifetime of hole τ_p is extremely short. Thus $\sigma_n^0 \ll \sigma_p$, i.e., $\tau_n^0 \gg \tau_p$. Since the lifetime of the holes injected from the anode is far less than its transit-time t_p from A to K, holes only exist in the near anode region has little contribution to current conduction and base region conductance modulation. The current is just space charge-limited electron current[10] and directly proportional to the square of the voltage. However, double injection can't yet be formed at this stage.

(3) When V_A increases to the anode flatten barrier voltage $V_{A,f}$, the corresponding field $E_{A,f}$ goes through the whole device till the kathode[7]. So the barrier is flattened under the action of $E_{A,f}$ that results in the device entering into high-level injection fleetly. Here there are enough holes filling the centers (setting $p = 5\times10^{18}$ cm^{-3} $\gg N_t = 1\times10^{11}$ cm^{-3} $\gg p_0 = 4.5\times10^6$ cm^{-3}). In other words, because the holes in the valence band are abundant enough to absorb all of the electrons in the centers, the centers become neutral state from originally negative electric state. Therefore the σ_p becomes smaller and smaller, whereas τ_{ph} increases constantly, i.e., $\tau_{ph} \gg \tau_p$. All of these are the consequences of the high-level effect. Therefore it is possible that (a) holes can transit across the whole base region till the cathode; (b) the double injection can be formed; (c) the e–h plasma can be formed; and (d) two kinds of carriers both have contributions to current conduction and conductance modulation. When the concentrations of the holes and electrons are very high ($n \approx p \gg n_0 \approx N_D^-$), the main tendency in the base region is the recombination effect[9]. The speeds of recombination of holes and electrons can reach equilibration under the situation where all recombination centers are empty. Such a requirement is satisfied under the high-level injection. So we have

$$\tau_{ph} = \tau_{nh}. \quad (12)$$

When we calculate electron lifetime under high-level injection τ_{nh}, the concentration of the electron capturing centers is N_t. Hence τ_{nh} can be expressed by

$$\tau_{nh}=\frac{1}{\overline{v}_n\sigma_n N_t}, \quad (13)$$

where $\overline{v}_n$ is the average velocity of the electrons. τ_{ph} can be obtained by using Eq. (12).

$$\tau_{ph}=\frac{1}{\overline{v}_n\sigma_n N_t}. \quad (14)$$

The hole lifetime under low-level injection τ_p is described as

$$\tau_p=\frac{1}{\overline{v}_p\sigma_p N_t}, \quad (15)$$

where $\overline{v}_p$ is the average velocity of the holes. If we consider approximately that the field $E_{A,f}$ is large enough to make $\overline{v}_p=\overline{v}_n\to v_{th}$, the ratio of τ_{ph} to τ_p which corresponds to points F and B, respectively, is given by

$$\frac{\tau_{ph}}{\tau_p}=\frac{\sigma_p}{\sigma_n^0}. \quad (16)$$

At the situation of acceptor-like state recombination centers, σ_p/σ_n^0 is about 10^2–10^3. That is to say that along with the increase in injected level, the holes increase. Therefore the current also becomes larger and larger, resulting in τ_{ph} increasing quickly. So the transit of holes from the anode to the cathode becomes easy, and all of the injected holes from the anode have the transit capability to the cathode and contribute to current conduction and conductance modulation.

2.3.5. Base region conductance modulation

The increase in anode field and the variation in the contrastive relationship of the channel field flattened the barrier; the double injection is formed; the plasma with high density comes into being; the filling situation of the recombination centers varies from being occupied by electrons entirely to being empty, in other words, being occupied by holes entirely. The blockage to holes is relieved that leads to $\tau_{ph}\gg\tau_p$. All of these effects together get ready for deep conductance modulation.

2.3.6. Other effects

In addition, other effects such as the electric neutralization effect, recombination effect including recombination through centers and Auger recombination, space-charge effect, the change of mobility and drift velocity with injected electric level all have an influence on states transition. Here we are not going to give unnecessary details in this paper.

3. Conclusion

(1) The transition from blocking to conducting state occurs between two entirely opposite physical states with great disparity in nature. The physical nature and process of the transition are given with delicate analyses from six aspects and are discussed with new points of view.

(2) The characteristic of negative resistance is a special feature of the transition. The base conductance modulation is one of the key reasons. The authors point out that the conditions and physical mechanisms of conductance modulation are as follows. (a) The double injection of carriers, i.e., plasma injection. (b) The injection level should be high enough to make $n\approx p\gg n_0\approx N_D$. (c) The injected hole lifetime must be longer than their transit-time from A to K that results in that holes can transit the whole base region instead of being captured by recombination centers. (d) Change the filling situation to make the centers vary from negative state to neutral state. (e) Enhance the field to speed up the drifting velocity of the carriers.

(3) We also point out that the main physical effects correlated with the transition are as follows. (a) The enhancement of the anode field and changes of contrastive relationship of fields. (b) The barrier is flattened. (c) Five respective functions of injected electrons and holes during the process of transition are made clear. (d) The τ_{ph} is increased under the high-level injection whereas the σ_p is decreased instead.

(4) The given physical analyses including methods and points of views of the BTH are suitable for other barrier-type power devices.

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