Reverse Recovery Operation and Destruction of MOSFET Body Diode

Description

This document describes the reverse recovery operation and destruction of the MOSFET body diode.

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1. MOSFET body diode

The MOSFET has an intrinsic body diode (also called a parasitic diode) between the drain and source electrodes as an integral part of its structure. In Figure 1, the n^+ and p^+ (p-base layer) of the source electrode side are short-circuited by the source electrode. Consequently, besides the MOSFET structure, the p-base layer, the n^- drift layer, and the n^+ substrate form a PIN diode between the drain and source electrodes, which acts as a body diode.

Typically, the PIN diode (i.e., a diode with a p^+–n^-–n^+ structure) has four states. These are compared with the following MOSFET operations.

a. Reverse-blocking state

⇒ The MOSFET is in the cut-off region (OFF mode) in which the forward voltage is blocked.

b. Turn-on (forward recovery) state

⇒ Current starts flowing to the body diode.

c. Forward-conduction state

⇒ Current flows from the source to the drain of the MOSFET (via the body diode in the forward direction).

d. Turn-off (reverse recovery) state

⇒A transition occurs from the forward conduction of the body diode to the application of voltage across the drain and source of the MOSFET (OFF state).

State d differs from the typical on-to-off transition of a MOSFET in that a forward current is flowing through the body diode immediately prior to the transition. Therefore, the n^- drift layer is saturated with hole and electron carriers (conductivity modulation).

If the drain is positively biased relative to the source while in this state (i.e., while the body diode is forward-biased), the body diode is reverse-biased and transitions to the reverse recovery mode according to the applied voltage.

When a MOSFET is used as a simple switch, a reverse bias is never applied across the drain and the source, and therefore the body diode does not conduct. However, in resonant power supplies and inverter circuits, current can flow through the body diode during freewheeling and synchronous rectification operation.

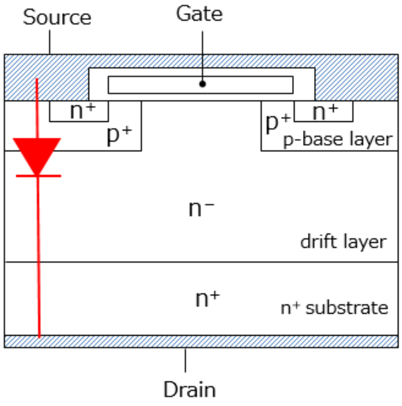

Figure 1 Body diode in a MOSFET

2. Reverse recovery

A diode exhibits considerable loss during reverse recovery, i.e., while it switches from the forward-biased state to the reverse-biased state. In the forward-biased (i.e., current-conducting) state, a large amount of electron and hole carriers is injected into the drift layer. When a diode is reverse-biased, carriers are swept out of the drift layer until the forward current becomes zero. During this process, a large recovery current flows through the diode in the reverse direction. This current causes a large reverse recovery loss. During forward recovery, only carrier injection occurs. Since a large current does not flow, forward recovery exhibits less loss than reverse recovery. Figure 2 shows the reverse recovery waveform of the body diode.

Reverse recovery is a process during which the application of a reverse bias (i.e., a positive potential to the drain electrode) causes a body diode in the forward-conducting state to switch to the reverse-blocking state (sweeping-out of the injected carriers), causing a reverse recovery current to flow. This process continues until the reverse recovery current becomes zero. In contrast, in the forward-biased state, holes are injected from the p-base layer connected to the source and flow to the drain whereas electrons are injected from the n^+ substrate connected to the drain and flow to the source.

Reverse recovery operation (#1 to #4 in Figure 2)

During #1

The body diode switches to the reverse-biased state according to external circuit conditions. Its forward current (I_F) decreases with a slope of $-di_F/dt$ until the injection of minority carriers (holes) stops and the forward current becomes zero. At this time, a lot of carriers remain in the n^- drift layer. $-di_F/dt$ is independent of the body diode characteristics and is determined by external circuit conditions such as the applied voltage, the reactance of the closed loop, and the turn-on speed of the switching device.

During #2

The body diode is in the reverse-biased state due to the external circuit conditions (i.e., the drain electrode has a positive potential relative to the source electrode). The holes remaining in the n^- drift layer are transported to the source electrode whereas electrons are transported to the drain electrode. As a result, a current flows through the body diode in the reverse direction. A sharp $-di_F/dt$ slope causes the carriers to be accelerated and exit the n^- drift layer quickly and therefore increases the peak reverse current. Because the drain-source (cathode-anode) path remains in a low-impedance state until the carriers are swept out of the n^- drift layer to a certain extent, the drain voltage remains low.

During #3

As the carriers exit the n^- drift layer, the drain voltage begins to increase at a certain point. This enlarges the depletion layer[*1] between the p-base and n^- drift layers. The drain-source (cathode-anode) path exhibits high impedance and sustains reverse voltage. As reverse voltage increases, the number of carriers swept out of the n^- drift layer decreases. Therefore, reverse current decreases. This voltage slope (dv/dt) is in inverse proportion to the capacitance of the depletion layer (C_{ds}).

During #4

Even after the width of the depletion layer reaches the limit, a current continues flowing until the carriers remaining near the MOSFET cell and the end of the n^- drift layer are swept out.

Without a large forward current (i.e., strong carrier injection), the #4 slope might not be observed.

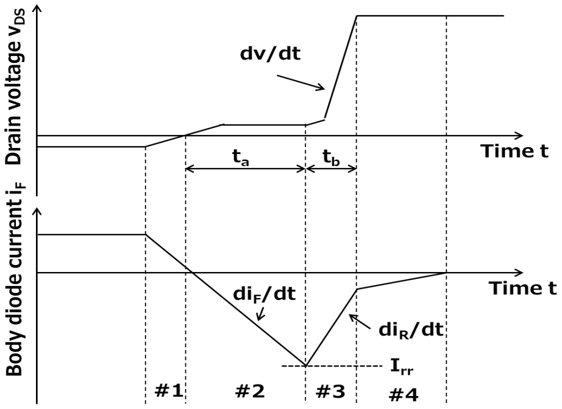

Figure 2 Reverse recovery waveform of the body diode

The current peaks when the body diode switches from #2 to #3. This peak current is specified as the reverse recovery current (I_{rr}). The ratio of the length of #3 (t_b) to the length of #2 (t_a), i.e., t_b/t_a, shows the reverse recovery softness. Soft recovery, i.e., recovery with large t_b/t_a, has low di_R/dt and dv/dt and thus exhibits low recovery noise during #3. I_{rr} and the reverse recovery softness (t_b/t_a) vary with the current slope (di_F/dt) during #1 and #2.

The integral of current over the period from #2 to #4 represents the amount of charge swept out of the n^- drift layer, which is called the reverse recovery charge (Q_{rr}).

3. Destruction of the body diode during reverse recovery

During reverse recovery, a high voltage (i.e., a high electric field) is instantaneously applied to the body diode, which causes high carrier concentration. In this state, a power loss could concentrate in a small spot due to uneven carrier distribution as it occurs in the event of a large avalanche current[*2]. If this happens, the body diode could be destroyed. This section describes the mechanism of body diode destruction.

The higher the carrier concentration in the drift layer, the greater the charge injection, and thus the intensity of the electric field changes. As described above, a sharp $-di_F/dt$ slope causes the carriers to be accelerated and exit the n^- drift layer quickly. Therefore, a sharp $-di_F/dt$ slope reduces reverse recovery time. Each carrier moves over different distances and with different ease. As a result of a shorter reverse recovery time, more carriers remain in the drift layer without being swept out. Residual carriers cause an electric field to concentrate in the small spot from which they exit the drift layer, leading to diode destruction. Therefore, the larger the di_F/dt value, the more susceptible a diode is to reverse recovery destruction.

Mechanism of reverse recovery destruction

The drain-source voltage (V_{DS}) increases sharply after the diode current decreases to a certain level (#3 to #4 in Figure 2). This high voltage is a major cause of body diode destruction. In this state, carriers in the MOSFET cell have almost disappeared whereas carriers still remain near the end of the n^- drift layer. All the holes remaining at the end of the n^- drift layer concentrate near the end of the p-base in the periphery of the MOSFET cell before being transported to the source.

This hole concentration causes a change in the electric field distribution (exceeding the critical electrical field strength), which leads to local avalanche breakdown[*2], destroying the device. In that case, the trace of destruction is observed at the end of the n^- drift layer.

During the application of a static voltage, a MOSFET has only carriers introduced by doping[*3]. Therefore, the charge near the end of the n^- drift layer is low (with only positively charged donor ions present). Consequently, the depletion layer extends horizontally, reducing the electric field at the end of the p-base. (Since the depletion layer extends into the n^- layer with low carrier concentration, the applied voltage is sustained only by the depletion layer. Therefore, during the application of a static voltage, the p layer has an equal electric field immediately below the cell and at the end of the n^- drift layer.)

In contrast, during reverse recovery, there are many positively charged holes near the end of the p-base as shown in Figure 3(b), making it difficult for the depletion layer to expand, as is the case with the end of the n^- drift layer having high dopant concentration. As a result, the electric field at the end of the p-base increases ($E = V/d$, where E is the electric field, V is the applied voltage, and d is the depletion depth). When the electric field exceeds the critical value, avalanche breakdown occurs at a voltage lower than the static breakdown voltage. An increase in current due to avalanche breakdown generates negative resistance, which causes current concentration, leading to device destruction.

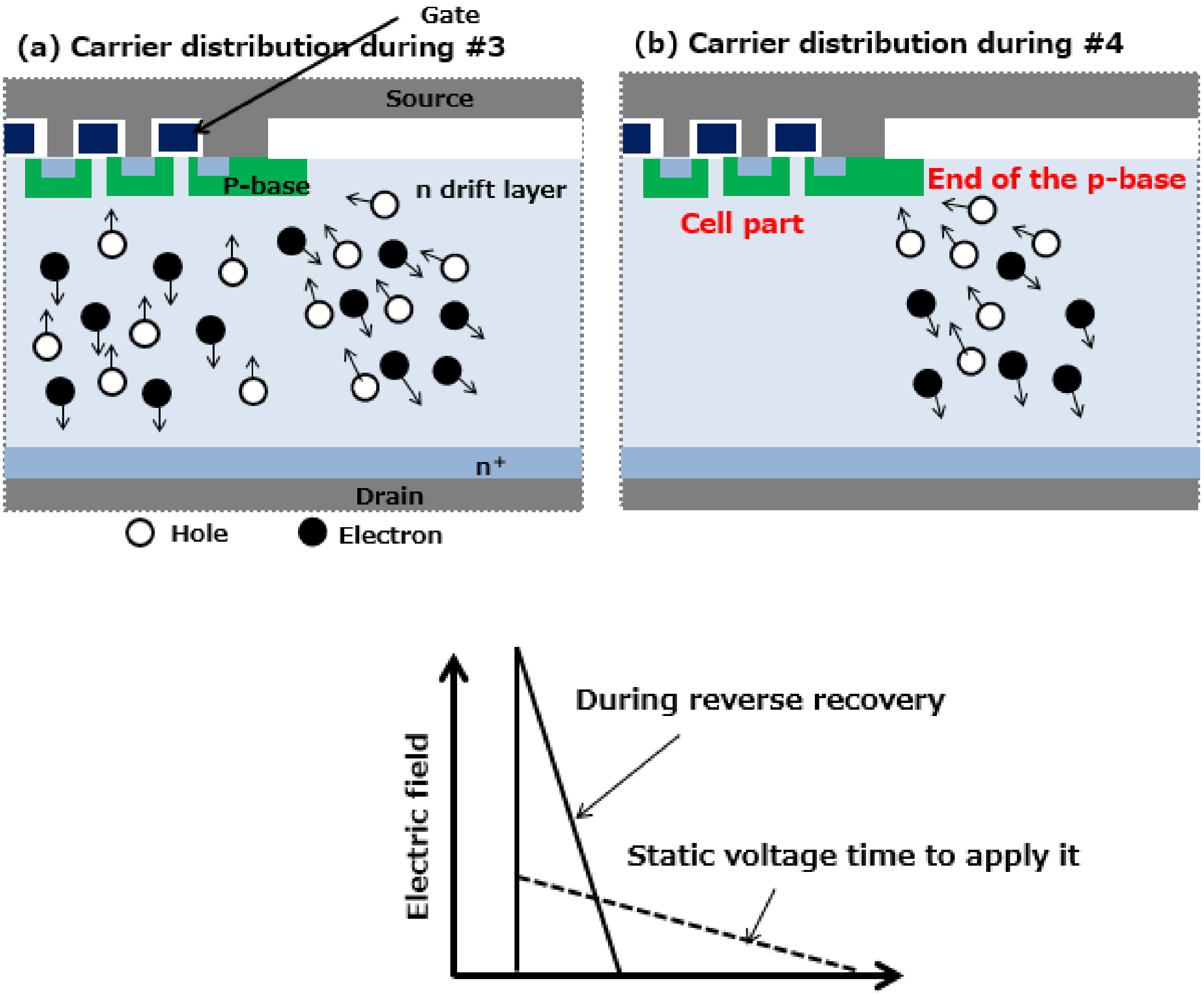

Figure 3 Difference between carrier distribution during recovery and electric field distribution during recovery and static voltage application

***1 Depletion layer**

Region where most electrons and holes have been diffused away by an electric field

***2 Avalanche breakdown**

A small amount of carriers (electrons) are moving through the depletion layer. These electrons are accelerated by an electric field and acquire large kinetic energy. The free electrons collide with the atoms of the crystal lattice, knocking out valence electrons from the atoms and creating electron-hole pairs. The resulting free electrons are also accelerated to high enough speeds to knock other bound electrons free, creating more free electrons and leading to further "knocking-out" processes.
This phenomenon is called avalanche breakdown, and the current generated by avalanche breakdown is called avalanche current. The electric field at which avalanche breakdown occurs is called the critical electric field.

The voltage at which avalanche breakdown occurs is called the breakdown voltage, which depends on the electric field distribution. Therefore, the breakdown voltage depends on the critical (maximum) electric field, the dopant concentration that determines the electric field slope, and the resulting thickness of the depletion layer (drift layer).

*** Doping**

Intentional introduction of impurities (i.e., dopants) into a semiconductor device

*** Donor**

A donor is a dopant atom that, when added to a semiconductor, donates an electron to form an n-type semiconductor. In contrast, an acceptor is a dopant atom that, when added to a semiconductor, donates a hole to form a p-type semiconductor.

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