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Dynamic and Static Characteristics of MOS Thyristors Irradiated with Electrons

EUGENIE V. CHERNYAVSKY[1], VLADIMIR P. POPOV[1], YURI S. PAKHMUTOV[2], YURI S. KRASNIKOV[1] and LEONID N. SAFRONOV[1]

[1]*Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences, Pr. Akademika Lavrentyeva 13, Novosibirsk 630090 (Russia)*

[2]*Angstrem Co., Yuzhnaya promzona, Zelenograd, Moscow 103460 (Russia)*

E-mail: evgen@isp.nsc.ru

Abstract

The results of development and manufacture of MOS controlled thyristors (MCT) are presented. Static and dynamic characteristics are studied. The effect of the irradiation with electrons on the static and dynamic characteristics is investigated. It is found that the irradiation with electrons provides a substantial decrease of the MCT turn-off time. Also an increase of the density of controllable current was observed.

INTRODUCTION

A new generation of bipolar field-effect devices of power electronics with blocking voltage up to 4.5 kV is rapidly developing. These devices include MOS controlled thyristors (MCT), emitter-switched thyristors (EST), insulated-gate bipolar transistor (IGBT), injection-enhanced gate transistor (IEGT). The combination of low voltage drop in the open state and the advantaged of field effect bring these devices among the most promising ones in power electronics. Unlike the gate turn-off thyristors (GTO), MCT and IGBT do not require large control circuits. The most difficult process for power devices is turn-off because current densities reach 100 A/cm^2. At these current densities, local nonuniformities may arise that can lead to current pinching and, as a consequence, to malfunctioning. Another critical parameter is turn-off time, which determines the dissipated power in the device during turn-off. The main methods to decrease turn-off time are anodic bypassing and controlling the carriers lifetime by adding recombination centers. One of the methods to add recombination centers is the irradiation with electrons. This technology is successfully used to decrease the dynamic losses in GTO thyristors. In bipolar field-effect devices, this irradiation causes worsening of the parameters of controlling MOS transistors and can lead to the decrease of the controllable current, and thus to the decrease of the region of safe operation.

The goal of the present investigation was to study the possibility to control the turn-off time of MCT with anodic bypassing, and to study static and dynamic characteristics of the devices with different lifetimes of carriers in N base.

EXPERIMENTAL

Anode structure

In order to achieve the breakdown voltage of 2.5 kV in combination with low voltage drop in the open state, anode buffer n layer in combination with anodic bypasses was used in MOS thyristors, similarly to high-power GTO [1–3] (Fig. 1). The plates of crucible-free zone-melted silicon 420 μm thick and specific resistance of 2000 Ω cm were selected as the initial material. The buffer N layer of the anode was formed by the diffusion of phosphorus to the

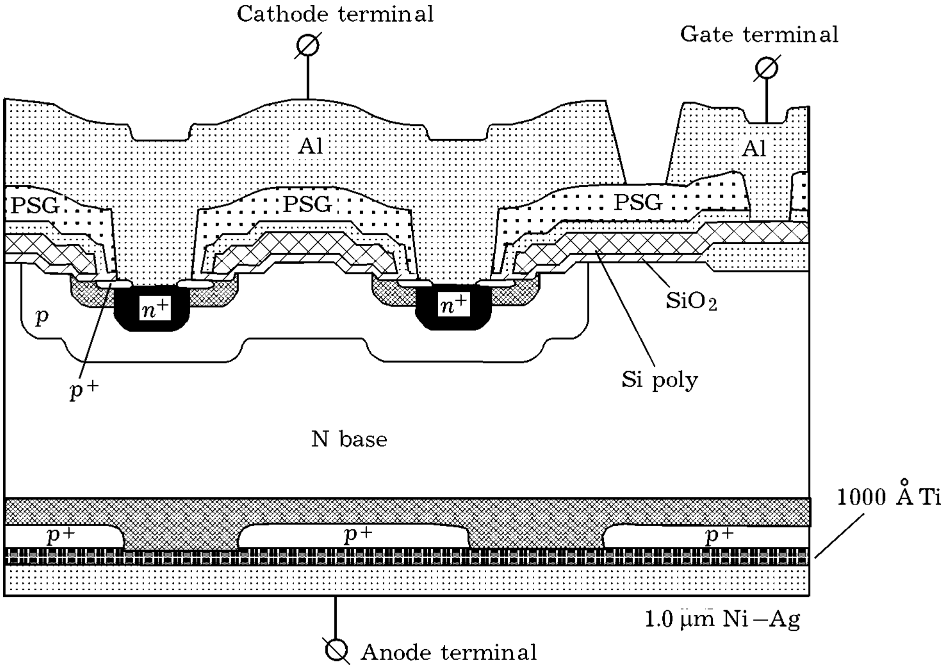

Fig. 1. The structure of MOS thyristor.

depth of 15 μm. The anodic p^+ emitter was formed by implanting boron through the photoresist mask followed by dispersal to the depth of 1 mm. Windows were left in the layer of the anodic p^+ emitter for the metallization of the contact of the anode to the layer of the anode buffer. Thus the anodic bypasses were formed. The ratio of the area of the emitter contact S_{p^+} to the area of the contact to N buffer S_n was 100 : 1. The procedure of anode preparation was described in [4–6]. The metallization of anode is multilayer. The first layer is composed of Ti 1000 A thick. Then the layers of Ni and Ag are deposited, their total thickness being 1 mm. This metallization is necessary for soldering the crystal into the housing onto the tin-lead solder. The structure of the anode is shown in Fig. 1.

The structure of the cathode

MOS thyristors is a bipolar device with field control. Because of this, N channel MOS transistors used to switch on the thyristors are placed on the planar side of the MOS thyristors, and the P channel MOS transistors used to turn the thyristors off.

The cathode looks like a matrix of the unit cells 80×80 μm composed of 24 N emitters located in the P well. The well to the N base is in the center of the unit cell. It is a drain of the turning-on N channel MOS transistor. P^+ regions are situated along the periphery of the emitter. These regions are the sources of P channel turn-off transistors, made as a ring. The ring P^+ sources also have a contact to the metallization of the cathode. The length of the channel of P channel transistors is 0.8 mm. The drain for it is a P pocket. The distance between N emitters is 6 μm. N emitters are manufactured by implanting phosphorus according to the self-combined technology through a polysilicon mask. P^+ source is also implanted through polysilicon mask. Polysilicon is at the same time the common gate for the N and P channel MOS transistors. Polysilicon is doped with phosphorus till the resistance R_s = 12 Ω/square. P pocket is common for all the N emitters; it is rectangular with the dimensions of 7820×4820 μm. The total number of N emitters is 144 042. The length of the emitter perimeter is 40 mm, so the W/L ratio for P channel MOS transistors is 50. Total width of the channels of all the P channel MOS transistors is 5.76 m. Total number of N channel MOS transistors is 5901. The channel length is 9 μm, total width W is 0.354 m. The contact to the polysilicon gate of the transistors is on a separate plate. Interlayer insulation of the aluminium of cathode and polysilicon of gate is made of the phosphorosilicate glass. The structure of the cathode of MOS thyristors is shown in Figs. 1 and 2.

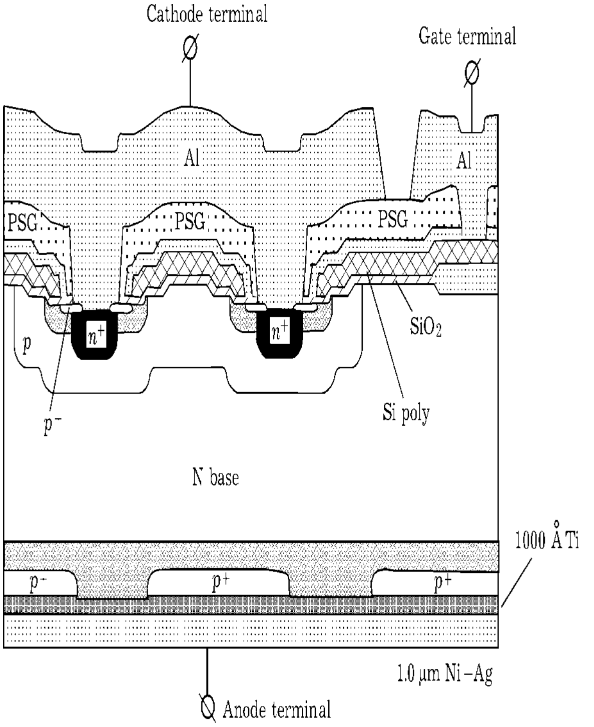

Fig. 2. The structure of the cathode of MOS thyristor.

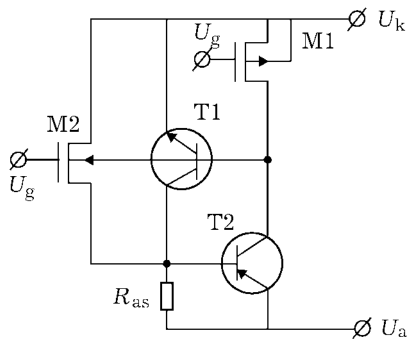

Fig. 3. Basic equivalent circuit of MOS thyristor.

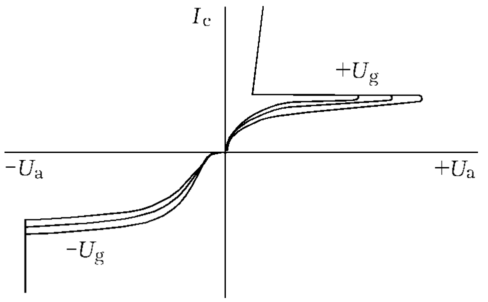

Fig. 4. Static voltage-current characteristics of MOS thyristor with anodic bypass. Voltage at the gate U_g (1–15 V) is positive for the direct branch and negative (−5 ... −20 V) for the inverse branch.

Basic equivalent circuit

In order to describe the processes in MOS thyristor, let us turn to the basic equivalent circuit shown in Fig. 3. In this circuit, bipolar transistors T1 and T2 are a vertical NPNP structure. This structure physically consists of the layers of MOS thyristor: N^+ emitter–P pocket–N substrate–P anode. It is modeled by a composite NPN–PNP transistor in which the base of the transistor T1 is connected with the collector of the transistor T2. N-channel MOS transistor M2 is intended for turning the thyristor on. When positive voltage is supplied to the gate, the transistor M2 injects carriers into the N substrate, which is a drain for the transistor M2; positive feedback in current is formed between the T1 and T2 transistors; the thyristor is turned on. To turn the thyristor off, it is necessary to break this positive feedback. In MOS thyristor, this is achieved by opening p-channel in MOS transistor M1, the drain of which is P pocket. The current of holes drains along the P^+ channel to the source, which is connected with N^+ emitter by metallization. Thus, a bypass channel appears; the excess carriers drain along it to the cathode, and the thyristor gets turned off. The ability of the thyristor to get turned off is critically dependent on the parameters of the turning-off P channel MOS transistor. The resistance Ras between the base and the emitter of the transistor T2 is the resistance of the anodic bypasses.

Static voltage-current characteristics of the MOS thyristor

MOS thyristor with anodic bypass is a unipolar device. Static voltage-current characteristics (VCC) of the MOS thyristor are shown in Fig. 4. At the positive voltage on the anode and negative or zero at the gate, MOS thyristor blocks the current from cathode to anode. When positive voltage is supplied to the gate (with respect to the cathode), one can see the family of the characteristics of N channel MOS transistor that switches the MOS thyristor on. When the cathode current reaches the holding current of thyristor, latching occurs. At this region of VCC, the cathode current is determined by the dynamic resistance of the thyristor $R_{\mathrm{ds\ (on)}}$. Let us consider the inverse branch of the characteristic at the negative voltage U_{a} and negative (with respect to cathode) gate voltage $-U_{\mathrm{g}}$. Since the anode of the thyristor is made with anodic bypass, the transition {anodic P^{+} emitter – N^{+} buffer} is not blocking. In this case, the cathode current goes through the channel of the turn-off P channel MOS transistor, directly shifted transition {P pocket – N base} and through the resistance of the anodic bypasses to anode. This region of the VCC is not working, but it allows controlling important parameters of the turning-off P channel MOS transsitor. At the working region (at positive U_{a}) and gate voltage $U_{\mathrm{g}} \leq 0$, blocking voltage reached 2500 V at the leakage current I_{leak} = 100–200 μA. Voltage drop in the open state was 2.8 V at the current of 32 A.

Dynamic characteristics

The dynamic characteristic of non-irradiated MOS thyristor is shown in Fig. 5. The anodic current increases to 19 A within 3.5 μs. The shutoff front consists of two phases, fast and slow. During the fast phase, the anodic current drops down to 10 % of the initial value within 1.5 μs. During the slow phase, the residual anodic current drops down within 30 ms. This is connected with long lifetime of the carriers in the high-resistance N base (~50 μs). Energy losses for turn-off are 80 mJ. To decrease the duration of the turn-off front, and consequently dynamic losses, different methods of decreasing the lifetime of carriers are used. One of these methods is the addition of radiation defects acting as recombination centres. To achieve this purpose, the irradiation with γ-quanta [7], electrons [8, 9] and protons [10] is used. Each of these methods has its own physical and technological features. The irradiation with protons is applied before the plates are separated into chips and placing into the housing; irradiation with γ-quanta and electrons is possible for devices already placed in the housing. In the case under consideration, MOS thyristor was placed into the TO-218 housing; this means that only the irradiation with electrons and gamma-quanta was possible. Electrons with the energy of 2 MeV were used for irradiation. The irradiation dose was $5 \cdot 10^{12}$ cm^{-2}. After irradiation, MOS thyristors were annealed at 250 °C for 1 h. Voltage drop in the open state increased in irradiated MOS thyristors; it reached 7.5 V att he anodic current of 34 A, which corresponds to current density 100 A/cm^2. The duration of the turn-off front at the current of 33 A was 2.5 μs. Dynamic losses for turn-off were 35 mJ. Maximal density of turn-off current exceeded 150 A/cm^2. The dynamic characteristic of the irradiated MOS thyristor is shown in Fig. 6.

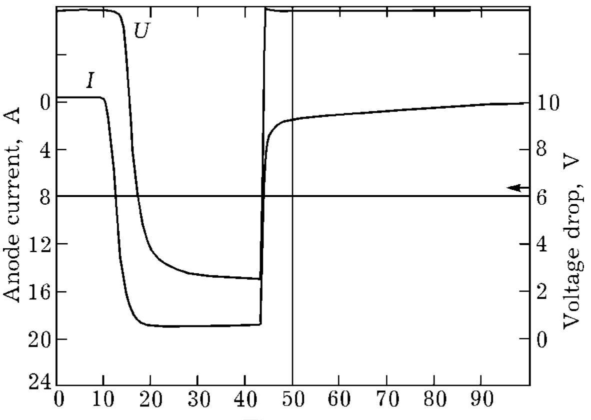

Fig. 5. Dynamic characteristics of non-irradiated MOS thyristor.

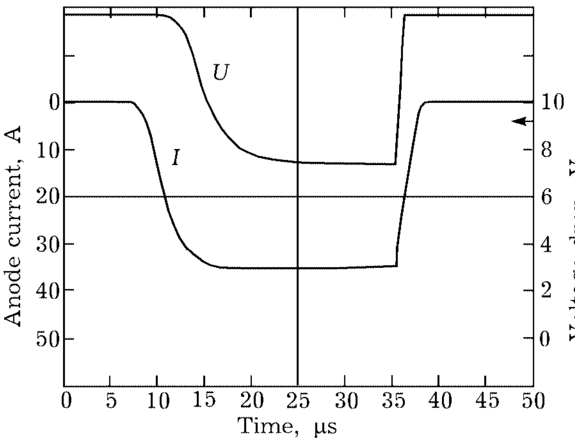

Fig. 6. Dynamic characteristics of irradiated MOS thyristor.

RESULTS AND DISCUSSION

The above results demonstrate that after irradiation the voltage drop in the open state increases. To explain the increase of voltage drop, we shall use the model of pin-diode. The applicability of this model for thyristor was demonstrated in [11]. Thyristor in the stationary conducting state is similar to pin diode with holes flowing from P emitter, and electrons flowing from N emitter. High density of electrons and holes leads to the conductivity modulation effect, which involves substantial decrease of the resistance of the thyristor N base. Voltage drop in the N base is described by the equation [11]

$$V_N = 8kTbd^2/[q(1+b)^2 D_a \tau_{eff}] \qquad (1)$$

Here D_a is the ambipolar diffusion factor, $b = \mu_n/\mu_p$ is the ratio of the mobilities of electrons and holes, $d = W_n/2$ is half-width of the N base, q is the charge of electron, τ_{eff} is efficient lifetime of carriers. According to [12], let us assume $D_a \sim 1$ cm^2/s, $d = 2.2\ 10^{-2}$ cm, $b = 3$, $\tau_{eff} = 50$ µs, $T = 100$ °C. Using the eq. (1) we obtain for non-irradiated thyristor: $V_N = 1.17$ V. The obtained value is two times lower than the observed voltage drop 2.8 V. However, it should be noted that here we do not take account of the voltage drop at the direct-shifted transition N^+ emitter − P pocket and voltage drop at contacts. For the lifetime $\tau_{eff} = 5$ µs in the N base of irradiated thyristor using the eq. (1) we obtain: $V_N = 5.4$ V. The observed voltage drop is 7.5 V. This shows that the voltage drop in the open state at the irradiated thyristor is to a larger extent determined by the lifetime of the carriers τ_{eff} in N base.

Besides the increase of the voltage drop, the increase of the maximal controllable current density was observed. No increase of the controllable current after irradiation and annealing was reported in literature. A possible explanation of the effect observed by us is as follows. The decrease of the lifetime leads to the decrease of the diffusion length L_p for holes. At $\tau_{eff} = 5$ µs, L_p becomes comparable with the distance between N emitters (~10 µm), which decreases the probability of switching hole current between the neighbouring N emitters. This leads to the weakening of current pinching effect at large cathode area and increase of the controllable current density. After irradiation and annealing, the controllable current density reaches ~150 A/cm^2 at total controllable current of MOS thyristor above 50 A.

CONCLUSIONS

The reported results demonstrate the possibility to control the turn-off front of high-voltage MOS thyristor within the range 50−1 µm and the improvement of its dynamic characteristics due to the decrease of dynamic losses during re-switching. A decrease of dynamic losses for turn-off by a factor of two has been achieved. Important result obtained in the investigation is a 2−3-fold increase of the maximal density of controllable current and broadening of the region of safe operation for the device. A possible explanation of the latter effect involves more uniform distribution of the hole current. However, when optimizing the duration of turn-off front, it is necessary to take account of the voltage drop in the open state and, as a rule, the increase of power losses in static regime.

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