Design Consideration for Structure of 2500-4500V RC- GCT

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Abstract

A basic structure of 2500V-4500V reverse-conducting GCT (RC-GCT) is given in this paper. The punch-through type (PT) is adopted for narrow N-base with high resistivity so that the fast turn-off and low on-state voltage can be achieved. The photo mask design was made upon the both turn-off performance and solution of separation between GCT and integrated freewheeling diode (FWD) part. The turn-on and turn-off characteristics for reserve-conducting gate commutated thyristors (RC-GCTs) were investigated by ISE simulation. Additionally, the local carrier lifetime control by proton irradiation was adopted so as not only to obtain the reduction of turn-off losses of GCT but also to reach a soft reverse recovering characteristics of FWD

Introduction

Recently, integrated gate-commutated thyristor (IGCT) is mostly interested as power semiconductor devices to compete with high power IGBT in the power electronics application such as traction drive, inverter and converter, static var compositor (SVC), pulse power circuit and so on. It is easy to manufacture GCT in low-cost bipolar device line, IGBT, however, has to be produced in high-cost MOS line. The use of IGCT is a suitable solution for parallel connection because of it's transistor's PNP turn-off mechanism, but gate turn-off thyristor (GTO) is not suitable for parallel connection because of PNPN thyristor's turn-off mechanism. In comparison to GTO, IGCT has the shorter storage time by fast turn-off switching, so GCT is very easy to make series connections for high–voltage power electronics development. To reach the desirable GCT device characteristics, we should consider following design factors:

- To reduce on-state losses and turn-off losses by minimizing silicon wafer thickness.
- To design anti-parallel freewheeling diode (FWD) capable of snubberless turn-off with high di/dt and soft recovery by adopting proper processes.
- To get fast turn-off performance of GCT upon improved switching properties of traditional GTOs.
- Monolithic integration of GCT and FWD without latch-up by minimized the lateral current flow of reverse recovery charges during reverse biases of FWD.
- Local carrier lifetime controlled by proton irradiation for superior device performance of power GCT and FWD.

In Japan and Europe, 6kV IGCT is now under development. Until now even there were some IGCT publications appeared elsewhere, but the core technology for GCT design itself has not been disclosed yet. In this paper, we have given the key design considerations for 2,500-4,500V RC-GCTs devices.

Basic Device Design

1) Bulk structure

RC-GCT devices are designed on n-type Si wafer of 63.5mm in diameter. It is noted that GCT should have a critical design consideration for robust extraction of carriers stored in N-base in comparable to commercial GTO structures. In this design, it is necessary to minimize the wafer thickness to obtain both of low on-state voltage and fast turn-off. We have designed punch-through structures on NTD (Neutron Transmutation Doped) wafers of high resistivity with 7% radial distribution. N-base thickness of Silicon wafer was determined in 220μm and 420μm for 2,500V and 4,500V devices, respectively, by means of simulation of reverse breakdown for pin diode shown in Fig. 1. The wafers for 2,500V and for 4,500V devices have 430Ω·cm and 550Ω·cm, respectively.

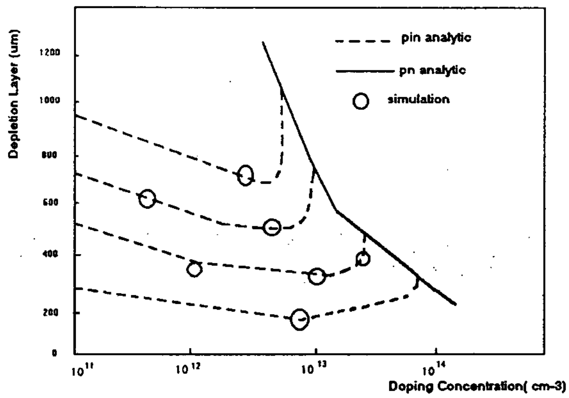

Fig. 1. The simulated results for W_n versus N_B of pin diode

2) Cathode finger

GCT's cathode finger of 280μm in width and 2.72mm in length is designed to turn-off peak current of 5A for each finger. Total 240 fingers are arranged on 3 concentric rings to achieve maximum turn-off current of 1,000A in snubberless operation and 2,000A with snubber capacitor of 3μF.

3) Key process

Fig.2 indicates the GCT cell with doping profile simulated by process simulation of DIOS of ISE. The P-base profile was formed by implantation of boron-aluminum in double-layer profile and then driven-in up to 102μm. A control of shallow aluminum profile is very critical to reach high blocking voltages. The oxidation with several percent of trichloroethylene (TCE) in oxygen ambient is very important to get long and uniform minority carrier lifetime. It is sure that this is helpful to get high turn-off ability.

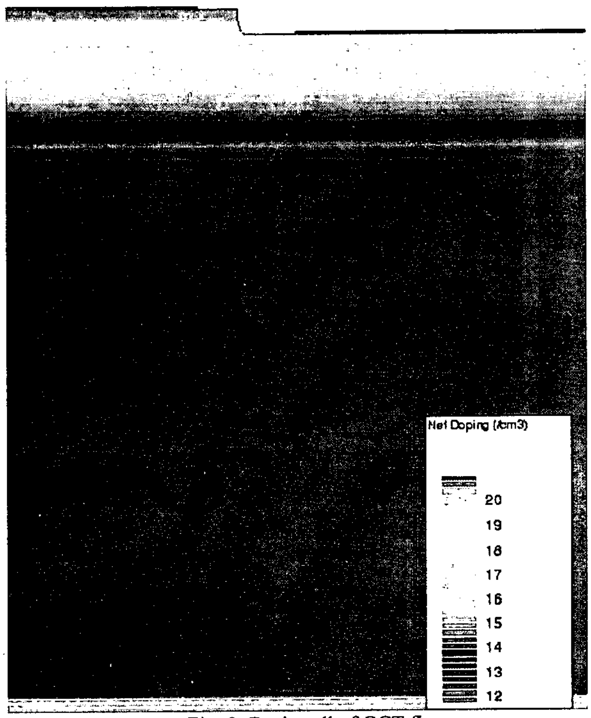

Fig. 2. Basic cell of GCT finger

An additional process for P^+ layer is adopted after recessed gate grooving so as to have a very low P-base sheet resistance which makes the GCT accommodate the negative turn-off current pulse with steeper rising rate ($-dI_G/dt$) to extract excess carriers more rapidly during turn-off transient. For the same purpose, a shallow gate groove about 10μm is made by wet chemical etching. Separated Al contact layers are evaporated 20μm and 10μm by the electron-beam evaporation for cathode and gate electrodes, respectively. This will guarantee the electrical isolation between gate and cathode. This process is quite different from conventional GTO's process.

4) Anode structure

The ring anode-short patterns on anode of GCT with interdigitated matrix of N^+ on P^+ instead of P^+ transparent emitter [1] is an optimized solution for easier mask process as well as fast turn-off. The author [2] reported that the ring anode-shorts structure results in uniform turn-off characteristics in usual GTOs of large diameter. Our improvement in this work will give more effective extraction of stored carriers, comparable to P^+ transparent emitter.

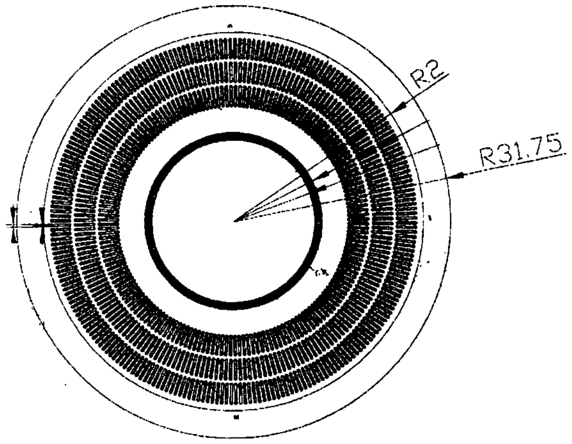

Fig. 3. Basic mask pattern for φ63.5mm RC-GCTs

5) Photo-mask design

On the other hand, as shown in Fig. 3, we succeeded to obtain photo-masks of RC-GCTs. In this work, we have designed 23mmΦ FWD in center of the die and GCT fingers in surrounding part of the die. Total 11 layers of photo-mask are needed for all processes in the fabrication of such devices. Special separation area of GCT and diode has been considered in the mask design. The effective diameter of device is 55mmΦ.

6) Simulation results for the switching transient

Fig. 4 gives switching waveform obtained from mixed-mode simulation by DESSIS of ISE. Fig.4 (a) shows turn-on waveform for I_A =250A when V_A=1,000V was applied. Fig.4 (b) shows turn-off waveform at anode current I_{TGQM} =170A when V_D =250V was applied. In this simulation, 30 fingers are connected in parallel by multiple-element mixed mode. Turn-off current I_{TGQM} is 170A, and storage time t_s is 0.2μs, therefore we have 850A/μs negative dI_G/dt. It is noted that at this moment the peak value of negative gate current is 170A, therefore, the typical GCT turn-off mode has been carried out. The total turn-off time is only 0.6μs and no obvious tail current is observed. This clearly indicates that the RC-GCT has a fast turn-off during switching transient. It is demonstrated that our GCT was conducted in transistor mode, as indicated in the low part of Fig.4 (b).

Integration and Optimization of FWD

There are two issues to be counterparts for monolithic integration of GCT and FWD parts into one wafer: One is to protect rushing currents from FWD into P-base of GCT during GCT's off-state phase. This rushing current may result in fault triggering to GCT. Another is to achieve softer reverse recovery characteristics of FWD. Otherwise, its hard reverse recovery will cause the tremendous turn-on overshoot current of GCTs, which may result GCT itself in permanent destroy.

We have proposed a novel technology for separation between GCT and FWD, as shown in Fig. 5. At the first step, separated P^+ layers of low resistance are diffused into P base of GCT and P emitter of FWD. Secondly a deep separation groove is etched down to P^+P interface in depth of 35μm. In this case, the sheet resistance of groove is so high that the lateral current flowing from FWD to GCT is almost blocked.

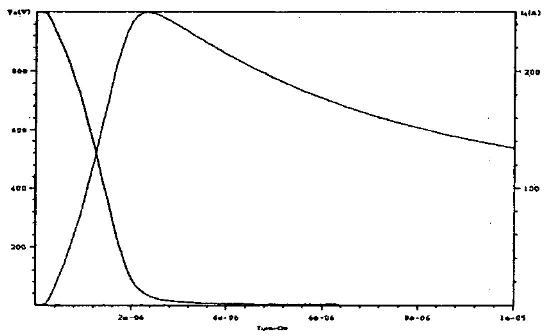

Fig. 4. (a) ISE simulated turn-on waveform at I_A 250A, V_A 1000V.

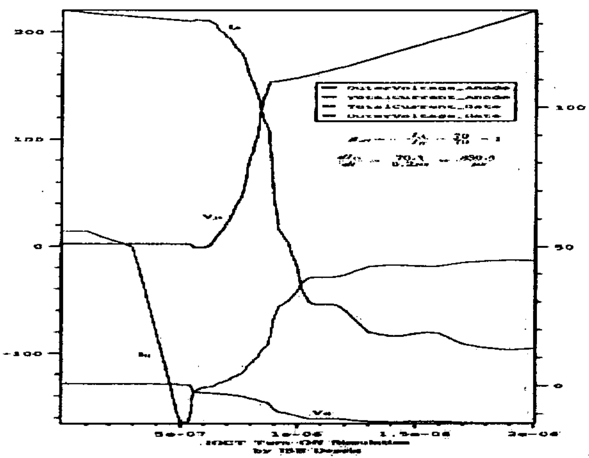

Fig. 4. (b) ISE simulated turn-off waveform at I_A 170A, V_A 250V. Note: turn-off gain $\beta_{off}=I_A/-I_G=170A/170A=1$.

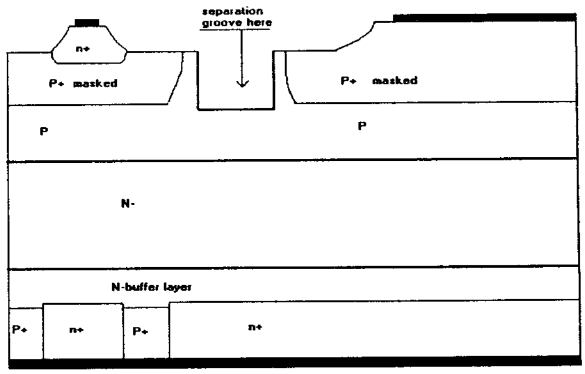

Fig. 5. A novel separation technology proposed for RC-GCTs.

In order to realize soft reverse recovery of FWD, local carrier lifetime control by proton irradiation is introduced to RC-GCT. Previous work [3] indicated that local carrier lifetime control by 5.0MeV proton irradiation in depth of 220μm for 1,000A/2,000V punch-through diode could have soft recovery characteristics of power diode produced in PERI. It is demonstrated that proton irradiation can considerably reduce the turn-off losses E_{off} to one third in comparison with conventional GCT.

Conclusions

The reverse-conducting GCT structures with 1,000A/2,500-4,500V ratings were designed by aid of ISE simulation. The basic design parameters and photo mask are given in this paper. We proposed a novel separation structure in between GCT and FWD. The realization of local carrier lifetime control by proton irradiation can considerably reduce the turn-off losses of GCT, and improve the soft recovery of freewheeling diode as well. By means of a series of improvements of key process, the fast turn-on and turn-off have been achieved in this GCT device.

Acknowledgements

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