**HV-P6**

# Study of the electrostatic potential of the floating-p region during the turn-on period of IGBT

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***Abstract*— In this work, the influence of the initial electrostatic potential value of the floating-p region, Vfp, on the controllability over the turn-on dIc/dt (Collector current increase rate) is studied using TCAD simulation. To investigate the influence of Vfp on the turn-on characteristics, a two-step calculation procedure is used. In the first step, the off state is calculated in which the floating-p region is connected to a fixed voltage source. In the second step, the turn-on characteristics are calculated in which a large resistance is connected between the floating-p region and the voltage source. In this manner, Vfp can be fixed at arbitrary value Vfix at the beginning of the turn-on period, and, then, becomes floating during the following period. The increase rate of the collector current becomes lower as Vfix increases because the high initial Vfp accumulates fewer holes in the floating-p region. And the mechanism that determines the initial Vfp is also analyzed. A hypothesis is set up that the off-state Vfp is equal to the threshold voltage of the P-channel MOSFET which consist of the floating-p, the n-drift, and the p-base region. To confirm the hypothesis, the relation between Vfp and major structural components such as the oxide permittivity, the oxide thickness, and the doping concentration are investigated. These results show a good agreement with the theoretical formula of threshold voltage of MOSFET.**

***Keywords*— *Insulated gate bipolar transistors, Floating P, Turn on, Controllability, Noise, Transient analysis***

## I. INTRODUCTION

It is well known that the IGBT with floating-p region has a poor controllability over the turn-on dIc/dt (Collector current increase rate) [1-3]. Figure 1 is the schematic diagram of how this process occur. As the channel is formed, electrons flow toward the n-drift region. And holes are injected from the Collector to the n-drift region. Holes gather in the floating-p region whose potential is lower than the Collector. The accumulation of holes increases the potential of the floating-p region, Vfp. The rapid increase of Vfp causes a displacement current, Idis, which flows into the gate electrode. Ideally the gate current, Ig, which would be limited by the gate resistance Rg, should govern the increase rate of the the gate potential. However, actually, the gate electrode facing the floating-p region is charged by Idis which is not limited by Rg. Thus it leads a poor controllability on the turn-on dIc/dt by Rg.

To overcome this drawback, some group proposed novel device structures which do not have the floating-p region [4, 5]. However, their fabrication process need additional immature processes.

Although this phenomenon is well known, the detail of the mechanism, such as the role of the potential of floating-p region has not been analyzed yet. In this work, the influence of the initial potential value of Vfp on the controllability over the turn-on dIc/dt is studied using TCAD simulation. And the mechanism that determines the initial Vfp is also analyzed.

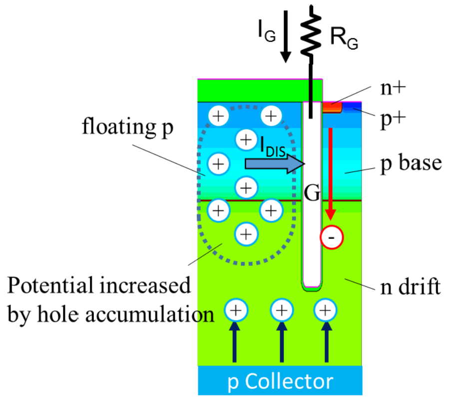
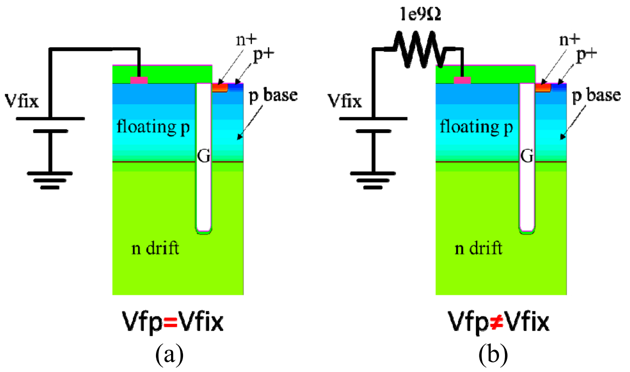


Fig. 1. Cross-section of IGBT with floating p region during turn-on period

## II. SIMULATION PROCEDURE

To investigate the influence of Vfp on the turn-on characteristics, a two-step calculation procedure is used as shown in Fig. 2. In the first step, the quasi-stationary off-state characteristics are calculated in which the floating-p region is connected to the constant voltage source, Vfix. In the second step, the transient turn-on characteristics are calculated in which a large resistance is connected between the Vfix and the floating-p region in order to substantially disconnect the floating-p region from Vfix. In this manner, the potential of the floating-p region Vfp can be fixed at arbitrary value Vfix at the beginning of the turn-on period, and, then, becomes floating during the following period.



Vfp=Vfix
(a)

Vfp≠Vfix
(b)

Fig. 2. Simulation procedure to fix the initial Vfp to Vfix and make it floating during the turn-on period

a) 1st step; off state with floating p connected to Vfx

b) 2nd step; turn on with floating p disconnected from Vfix

## III. RESULTS AND DISCUSSIONS

### A. *Results*

Figure 3 shows turn-on waveforms for various Vfix. The turn-on waveforms are drastically changed by Vfix value. The increase rate of Vfp, dVfp/dt, and dIc/dt becomes lower as Vfix value increases. Because the higher initial Vfp accumulates fewer holes in the floating-p region, Vfp increases less rapidly. The turn-on waveforms of the original IGBT with floating-p region (denoted as "floating" in Fig.3) are equivalent to that of Vfix = 11V. It is clear that this calculation procedure does not disturb the characteristics except the change of the initial Vfp value.

In Fig.4 the blue dotted line shows the relation between dIc/dt and Vfix. And the red solid line shows the dIc/dt for the IGBT with "non"floating-p region, where the p-region is connected to the Emitter potential. As Vfp increases, dIc/dt decreases and gets close to the value for the IGBT with nonfloating-p region. For example, the dIc/dt at Vfix=9V is twice higher than that at Vfix=11V. These results indicates that Vfix, which is initial value of Vfp at the beginning of turun-on period, has a significant influence on the turn-on dIc/dt.

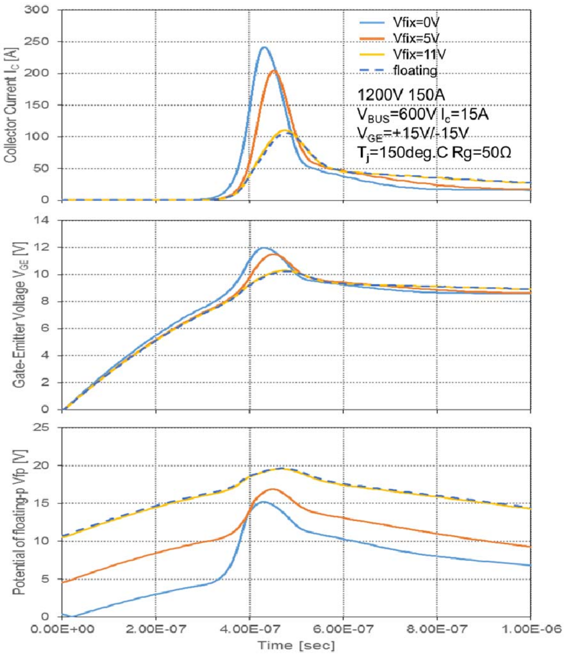


Fig. 3. Simulated turn-on waveforms for arbitrary initial potential of floating p region, Vfix

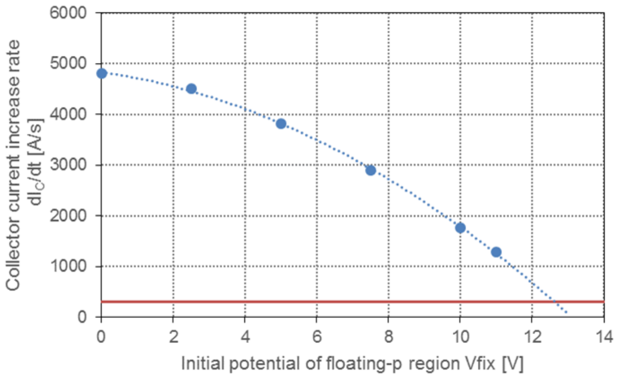


Fig. 4. Simulated dIc/dt as a function of Vfix

### B. *Mechanism*

It is important to reveal how the initial Vfp of the "real" floating-p region is determined during the off-state period in order to design IGBT with good turn-on controllability. A hypothesis is set up that the off-state Vfp is equal to the threshold voltage of the P-channel MOSFET which consists of the floating-p, the n-drift, and the p-base region (see Fig. 5). Even in the off-state condition, holes come from the Collector as the leakage current and pile up not only in the floating-p region but also in the n-drift region around the trench gate. As the piling-up holes raise the potential in this region, a P-channel layer forms around the trench gate. Since the excess holes flows to the p-base region via the P-channel, Vfp does not increase more. In this way Vfp takes a certain constant value.

To confirm this hypothesis, the relation between Vfp and major structural components such as the oxide permittivity, the oxide thickness, and the doping concentration are investigated.

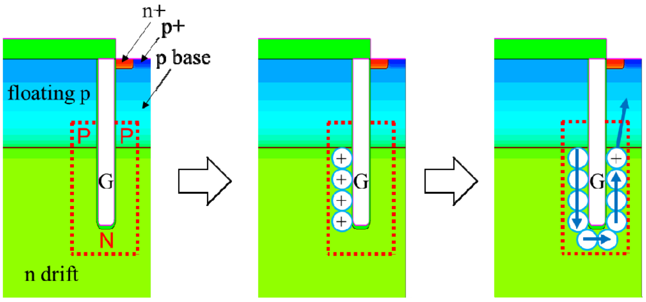


Fig. 5. Hypothetical mechanism which determine the initial potential of floating-p region. The potential rises until the P-channel layer forms around the trench gate.

### C. *Gate oxide permittivity*

First, the initial Vfp for various dielectric constant, K, of the gate oxide is investigated. To keep the Vth, only K at the bottom of the trench is changed where the Vth is highest. As shown in Fig. 6, the initial Vfp is linearly dependent on the reciprocal of K. This relation agrees with the formula of the theoretical relation between Vth and εox which can be expressed as

$$V_{th} = \frac{qN_D d \cdot t_{ox}}{K\varepsilon_0} + 2\phi_n \tag{1}$$

where $V_{th}$ is the threshold voltage, $q$ is unit electron charge, $N_D$ is donor concentration, $d$ is depletion width, $t_{ox}$ is oxide thickness, $\varepsilon_o$ is permittivity of vacuum, $\phi_n$ is Fermi potential in n-type semiconductor.

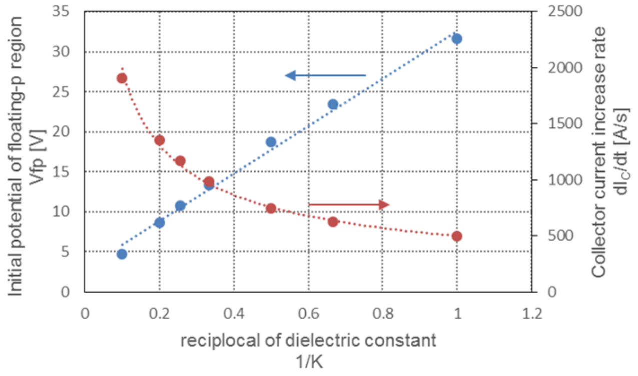


Fig. 6. Simulated Vfp and dIc/dt as a function of 1/K

### D. Doping concentration

Second, the initial Vfp for various doping concentration of the n-drift region is investigated. Figure 7 shows the relation between initial Vfp and the doping concentration. The initial Vfp has a linear dependence on the doping concentration that also corresponds to the equation (1).

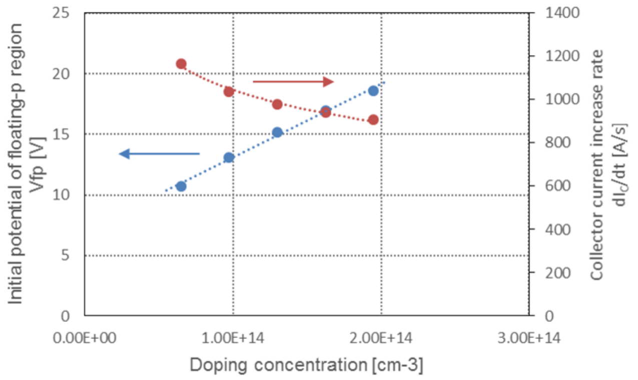


Fig. 7. Simulated Vfp and dIc/dt as a function of doping concentration

### E. Gate oxide thickness at the bottom of the trench gate

Last, the initial Vfp for various gate oxide thickness at the bottom of the trench is investigated using the device structure shown in Fig. 8. To keep the Vth, only the bottom thickness is changed. The initial Vfp has a linear dependence on the gate oxide thickness that also corresponds to the equation (1) as shown in Fig. 9.

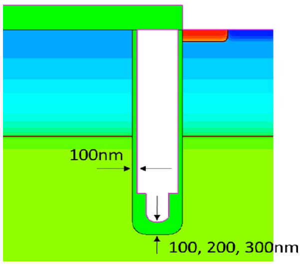


Fig. 8 Cross-section of IGBT with various thickness of bottom gate oxide

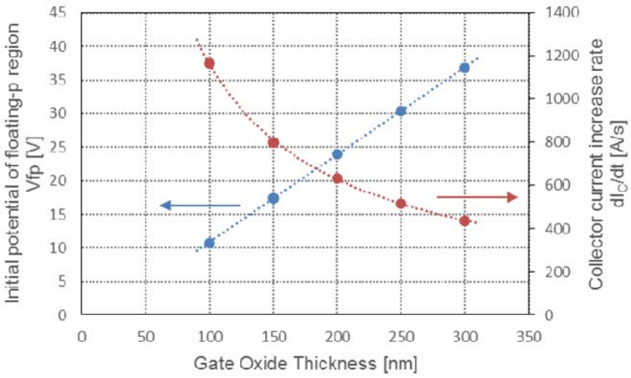


Fig. 9. Simulated Vfp and dIc/dt as a function of bottom gate oxide thickness

It is expected that the IGBT with thicker gate oxide at the bottom of the trench has a better controllability on the turn-on dIc/dt. Figure 10 shows the turn-on waveforms for 100 and 300nm of the gate oxide thickness at the bottom of the trench. The waveform for 100nm shows a rapid increase of the collector current Ic. This rapid increase occurs when the gate voltage suddenly changes the increase rate. As described earlier, this is because the displacement current charge the gate electrode rapidly.

Figure 11 shows the dIc/dt as a function of the gate resistance for different gate oxide thickness at the bottom of the trench. As expected, IGBT with 300nm trench bottom oxide shows a better controllability on the turn-on dIc/dt compared to that of 100nm one.

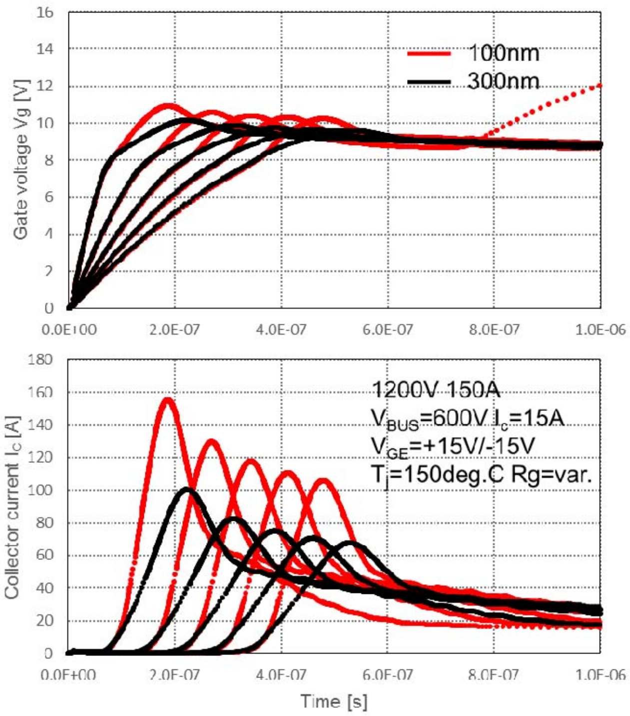


Fig. 10. Simulated turn-on waveforms for different bottom gate oxide thickness

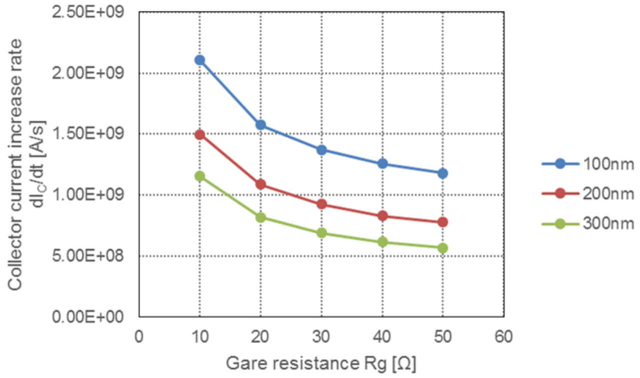


Fig. 11. Simulated dIc/dt as a function of Rg with different bottom gate oxide thickness

# IV. CONCLUSIONS

In this work, it is shown that the initial potential value of the floating-p region has a significant influence on the controllability over the turn-on dIc/dt. And the mechanism that determines the potential of the floating-p region, Vfp, is also analyzed. A hypothesis is set up that the off-state Vfp is equal to the threshold voltage of the P-channel MOSFET which consists of the floating-p, the n-drift, and the p-base region. To confirm the hypothesis, the relation between Vfp and major structural components such as the oxide permittivity, the oxide thickness, and the doping concentration are investigated. These results show a good agreement with the theoretical formula of threshold voltage of MOSFET.

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