K. Fuse et al., “Analysis of Recovery Oscillation Inhibition for Cathode Design of a 1200 V Silicon Diode Using an LCR Circuit Model”, Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials (SSDM), Virtual conference, 2020, pp261-262

Analysis of Recovery Oscillation Inhibition for Cathode Design of a 1200 V Silicon Diode Using an LCR Circuit Model

Kaori Fuse, Keiko Kawamura and Tomoko Matsudai
Toshiba Electronic Devices & Storage Corporation
1 Komukai Toshiba-Cho, Saiwai-ku, Kawasaki 212-8583, Japan
E-mail: kaori.fuse@toshiba.co.jp

Abstract

In this paper, the relationship between cathode N^+/P^+ design and the Q factor (quantified oscillation) is analyzed using an LCR circuit model in a 1200 V silicon diode. We confirmed that the width ratio of the cathode N^+ layer to the whole diode (the cathode N^+/P^+ layer) is involved in recovery oscillation phenomena. Despite different injection efficiencies from the cathode P^+ layer a correlation diagram can be described.

1. Introduction

A reverse conducting insulated gate bipolar transistor (RC-IGBT) was integrated with a diode in order to reduce the module size and chip cost. It is necessary to develop diode for RC-IGBT. The diode tended to have current and voltage oscillation because it had only a cathode N^+ layer. Cathode N^+/P^+ design in silicon diodes and an LCR circuit model has been studied previously [1-5]. At SSDM2019, we proposed mechanisms for analyzing diode design with an N buffer and cathode N^+/P^+ layer using an LCR circuit model to inhibit oscillation in reverse recovery [6]. The amplitude oscillation waveforms were found to depend on the Q factor, which indicates quantified oscillation for an LCR circuit model. The diode design consists of an N buffer with a cathode N^+/P^+ layer, the Q factor becomes small. The N buffer was effective for inhibiting expansion of the space charge region to the cathode side. The N^+/P^+ layer has the effect of shifting the maximum oscillation timing from high (maximum Q factor) to low (small Q factor) because of the injected holes from the P^+ layer. However, no study has investigated the relationship between cathode N^+/P^+ design and the Q factor (quantified oscillation). In this paper, we report the correlation between cathode N^+/P^+ design and Q factor (quantified oscillation) based on an LCR circuit model. We discuss that width ratio of the cathode N^+ layer relative to the whole diode and find that this ratio is involved in the oscillation condition, despite different injection efficiency conditions.

2. Device design and LCR circuit model

Figure 1 shows a schematic cross section of the proposed diode structure. The diode has a cathode N^+/P^+ layer with an N buffer. Here the width of cathode N^+/P^+ layer is half pitch. This study mainly examines different widths in the cathode N^+/P^+ layer and different P^+ doses under accurate conditions with a low state voltage (Vf). Figure 2 shows (a) the circuit used in the recovery simulation and (b) an LCR circuit model of the pin diode in reverse recovery. The diode is regarded as a capacitance (C) and two resistances (R_1, R_2). Using the LCR circuit model, the oscillation mechanisms are explained in Fig. 3 [5]. The oscillation is explained by oscillation frequency ω (Eq. 1) and the Q factor (Eq. 2). If ω is a real number, oscillation occurs. In particular, the crossing point ($R_2/L_S=1/CR_1$) that satisfies the oscillation condition exactly corresponds to the oscillation timing at Time A. In addition, the amplitude of the oscillation waveforms is proportional to the Q factor (Eq. 2).Our previous study revealed that oscillation is suppressed at Time A when the P^+ side of the cathode does not satisfy the oscillation condition (i.e., when ω is an imaginary number) and the N^+ side of the cathode satisfies the oscillation condition under adjusted hole injection efficiency conditions. We estimated that the oscillation is involved in both width ratio of oscillation area to the whole diode and the Q factor.

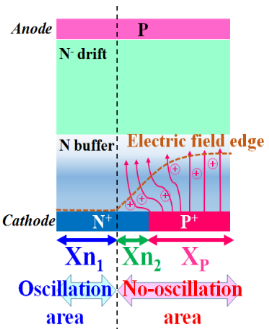


Fig. 1 Schematic cross section of the proposed

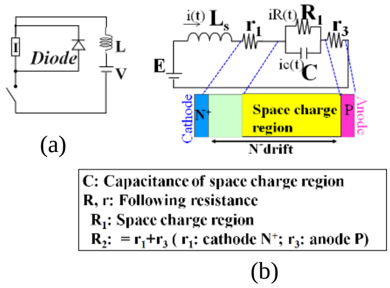
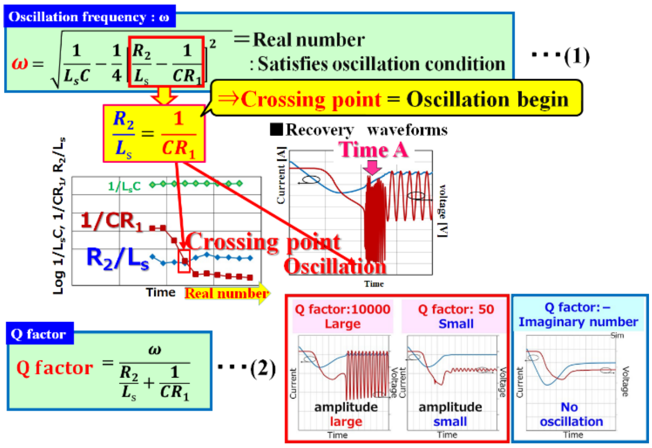


Fig. 2 (a) Circuit used in the recovery simulation
(b) LCR circuit model for a pin diode in reverse recovery



$$\omega=\sqrt{\frac{1}{L_sC}-\frac{1}{4}\left(\frac{R_2}{L_s}-\frac{1}{CR_1}\right)^2}\quad\cdots(1)$$

$$\frac{R_2}{L_s}=\frac{1}{CR_1}$$

$$\text{Q factor}=\frac{\omega}{\frac{R_2}{L_s}+\frac{1}{CR_1}}\quad\cdots(2)$$

Fig. 3 Definition of the oscillation condition

3. Results and discussion

3.1 Relationship between the width of the cathode N^+/P^+ layer and the oscillation condition

First, we discuss the relationship between the widths in the cathode N^+/P^+ layer and the oscillation condition in reverse recovery.

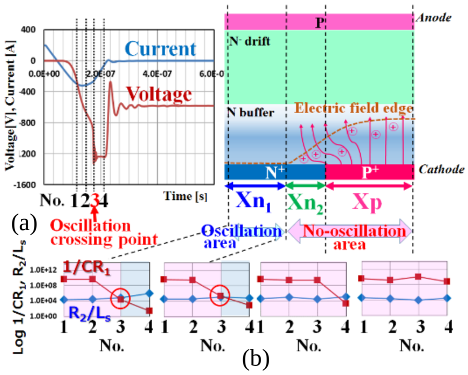


Fig. 4 (a) Simulated reverse recovery waveforms
(b) Calculated crossing point for No. 1-4 at various diode positions

Figure 4 shows (a) simulated current and voltage waveforms and (b) R_2/L_s and $1/CR_1$ from Eq. (1) at various positions in the proposed diode. The current and voltage oscillations can be observed at No. 3 (Time A) in Fig. 4 (a). In Fig. 4 (b), the horizontal axis corresponds to No. 1-4 in Fig. 4 (a) and the vertical axis shows R_2/L_s and $1/CR_1$. Xn_1 is where the oscillation condition (ω: real number) is satisfied on the N^+ side of the cathode at No. 3, where there is a crossing point. On the other hand, neither Xn_2 nor X_p has a crossing point at No. 3, meaning that the oscillation condition is not satisfied (ω: imaginary number) in these areas. The no-oscillation area includes not only the P^+ layer (X_p) but also part of the N^+ layer (Xn_2) because of the effect of injected holes from the P^+ layer.

Figure 5 (a) shows a correlation diagram the relationship between the width ratio of oscillation area and the Q factor. The horizontal axis shows the maximum Q factor. The vertical axis shows the width ratio of Xn_1 (oscillation area) to X_{all} ($=Xn_1+Xn_2+X_p$, the whole diode). Figure 5(b) and (c) shows simulated recovery waveforms. The correlation diagram can be classified into two main categories: an area with suppressed oscillation on the left and an area satisfying the oscillation condition on the right. In comparing N^+/P^+ = 50 µm/50 µm with N^+/P^+ = 60 µm/60 µm (i.e., the same width ratio of 1:1), the recovery waveforms for N^+/P^+ = 50 µm/50 µm show suppressed oscillation (Fig. 5 (b)) and a Q factor of 3000. In contrast, the recovery waveforms for N^+/P^+ = 60 µm /60 µm show the occurrence of oscillation (Fig. 5 (c)) and a Q factor of 9000. Thus, the Q factor changes if the widths of the cathode N^+ layer and the cathode P^+ layer are different even when their width ratio is the same. The injection of holes into the N^+ layer is influenced by the distance from the P^+ layer; if the N^+ layer is wide, the influence of hole injection from the P^+ layer is small.

Next, we examined the effect of P^+ dose on injection efficiency. As shown for Devices 1 and 2 in Fig. 5 (a), even when the widths in the cathode N^+/P^+ layer are the same (N^+/P^+=55 µm /55 µm), the device with a lower P^+ dose (Device 2) has a large Q factor. This causes that hole injection efficiency from P^+ layer decreases. No-oscillation area (Xn_2) becomes small. Thus the width ratio of the oscillation area (Xn_1) to the diode area (X_{all}) becomes large.

Therefore, the relationship between the width ratio of the oscillation area in the cathode N^+/P^+ layer and the Q factor is confirmed.

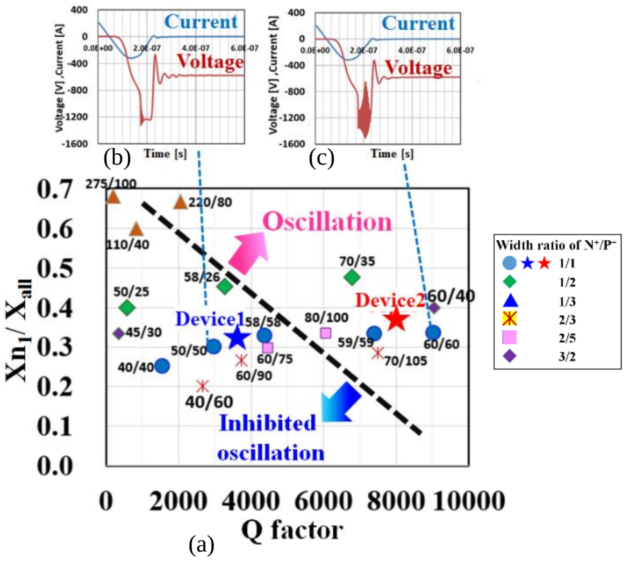


Fig. 5 (a) Correlation diagram of the relationship between the width ratio of the oscillation area and the Q factor
(b) Simulated recovery waveforms for the no-oscillation condition
(c) Simulated recovery waveforms for the oscillation condition

3.2 Experimental evaluation

Finally, we examined the influence of the oscillation area ratio in an experiment and evaluated the actual oscillation waveform. Figure 6 shows the measured current and voltage during reverse recovery. For N^+/P^+ = 60 µm/40 µm, which had a simulated oscillation area (Fig. 5), oscillation was actually observed. On the other hand, for N^+/P^+ = 40 µm /60 µm, which had a simulated no-oscillation area (Fig. 5), no oscillation was actually observed.

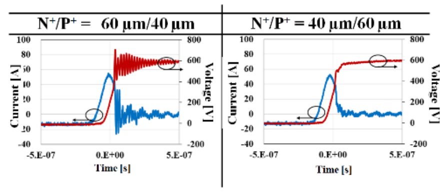


Fig. 6 Measured reverse recovery waveforms in a diode with cathode N^+/P^+ structures

4. Conclusion

We fabricated and analyzed the relationship between cathode N^+/P^+ design and the Q factor (oscillation) using an LCR circuit model. The oscillation was involved in both width ratio of Xn_1 to X_{all} and Q factor. Xn_2 was a no-oscillation area introduced in the N^+ layer. The results confirmed that the relationship between the width ratio of the oscillation area and the maximum Q factor defined a continuous oscillation condition despite different injection efficiencies for the ratio of the cathode N^+/P^+ layer or different P^+ dose. This analytical model appears to be applicable to RC-IGBTs containing diodes.

References

[1]K. Nakamura *et al.*, Proc. of ISPSD’09, pp.156-159. 2009
[2]F. Masuoka *et al.*, Proc. of ISPSD’24, pp.373-376.2012
[3]S. Matthias *et al.*, Proc. of ISPSD’25, pp.335-338.2013
[4]L.Pina *et al.*, Proc. of ISPSD’28, pp.303-305. 2016
[5]K. Satoh, *et al.*, Proc. of ISPSD’00, pp.249-252. 2000
[6]K. Fuse, *et al.*, Proc. of SSDM’19, pp.457-458. 2019