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A Study on the Design and Electrical Characteristics Enhancement of the Floating Island IGBT with Low On-Resistance

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Abstract – Insulated Gate Bipolar Transistors(IGBTs) have received wide attention because of their high current conduction and good switching characteristics. To reduce the power loss of IGBT, the on-state voltage drop should be lowered and the switching time should be shortened. However, there is trade-off between the breakdown voltage and the on-state voltage drop. The FLoatingIsland(FLI) structure can lower the on-state voltage drop without reducing breakdown voltage. In this paper, The FLI IGBT shows an on-state voltage drop that is 22.5% lower than the conventional IGBT, even though the breakdown voltages of each IGBT are almost identical.

Keywords: IGBTs, Floating island, On-resistance, Breakdown voltage, Power device

1. Introduction

Nowdays, power semiconductors are known as semiconductor devices operating on high voltage and high current levels excluding small signal devices. Individually, they are devices with a power consumption of over 1[W] such as diodes, BJT(Bipolar Junction Transistor), Thyristor, GTO(Gate Turn Off thyristor), DIAC(Diode for Alternating Current), power MOSFET(Metal Oxide Silicon Field Effect Transistor) and IGBT(Insulated Gate Bipolar Transistor). These semiconductors are critical for every electrical device that operates with power control or output control modules; automobiles, trains, communication equipments, home supplies, office supplies, and mobiles [1].

Power semiconductor devices should consume less power during the switching operation. Especially, IGBT has entered the spotlight, as it operates as a combination of MOSFET and BJT. This structure can drive high level current with low on-state voltage drop [2-4]. Featuring reduced power consumption in the system, IGBT has been developed to have a high breakdown voltage while maintaining its switching characteristics with a lower unit cost of fabrication. The high breakdown voltage property of the device is usually satisfied by doping the drift region at a lower level. However, this process causes higher on-state resistance, resulting in higher power consumption [2]. According to the development of the power electronics industry, the market is demanding power semiconductors that operate on higher voltage levels. And to obtain higher breakdown voltage, the n-drift length of the device must be extended, which causes higher on-state voltage drop. Therefore, an important theme throughout the field has been reducing on-state resistance and maintaining high breakdown voltage by optimizing and improving the structure.

Hence, this paper analyzed electrical properties of IGBT focusing on breakdown voltage and on-state voltage drop. Also, this paper suggested the Floating Island structure that can cause higher breakdown voltage without raising on-state voltage drop, by analyzing its electrical properties.

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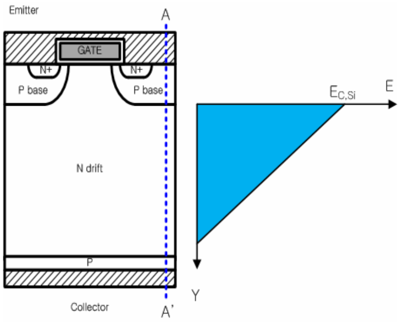
2. Theoretical Analysis and Simulation of FLI Structure

2.1 Theoretical analysis

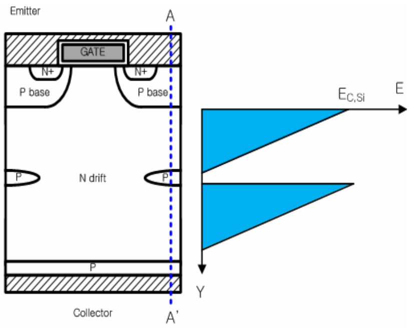
The Floating Island structure features the insertion of the P Floating Island into the low doped n-drift region. It was first introduced by N. Cezac, who applied it to the PIN diode and NPT IGBT(Vertical Diffused MOS) [5]. As shown in Fig. 1, the conventional NPT IGBT shows the electric field concentration between the p-base and n-drift region. On the other hand, FLI IGBT shows the dispersion of the electric field for the P Floating Island. As the breakdown voltage of the power semiconductor is proportional to the integration value of the electric field, both devices have the same breakdown voltage property. However, FLI IGBT has a higher doping concentration in the n-drift region, which has a lower on-state resistance compared to the conventional IGBT on-state resistance.

Eq. (1) can be applied to compare the electric field distribution of the device according to its y location.

$$-\frac{\rho_{charge}}{\varepsilon_s} = -\frac{dE(y)}{dy} = \frac{d^2V(y)}{dy^2} \tag{1}$$



(a) Conventional IGBT



(b) Floating Island IGBT

Fig. 1. Structure and electric field distribution of Conventional IGBT and FLI IGBT

Setting t as the thickness of the P Floating Island, $N_p$as the doping concentration and d as the distance from p-base, the off-state charge distribution of FLI IGBT is shown in Fig. 2(b). The charge distribution changes when it reaches the boundary between the P Floating Island and n-drift region. Therefore, different charge values should be substituted according to its regional location. The region is categorized in Table 1.

Table 1. Division of n-drift region according to the charge distribution

Region no.	Regional Setup	y-axis
(1)	P base ~ P Floating Island boundary	$0 \le y \le d$
(2)	Entire P Floating Island	$d \le y \le d+t$
(3)	P Floating Island edge ~ depletion layer edge	$d+t \le y \le W_d$

Finally, the electric field distribution equation can be determined by Eq. (2) using Table 1.

$$E(y) = E_{\max} - \frac{qN_d}{\varepsilon_s} y \qquad (0 \le y \le d)$$

$$E(y) = \frac{qN_p}{\varepsilon_s}(y-d) \qquad (d \le y \le d+t) \qquad (2)$$

$$E(y) = E_{\max} - \frac{qN_d}{\varepsilon_s}\{y-(d+t)\} \qquad (d+t \le y \le W_d)$$

Based on Eq. (2), the electric field distribution of the conventional and FLI IGBT with identical drift length is depicted in Fig. 2(c). The breakdown voltages of the two are identical, as the integration values of the electric field are identical. On the other hand, the gradient of the electric field in FLI IGBT is larger by a factor of 2 compared to the conventional NPT IGBT. As the gradient of the electric field is proportional to the doping level, the doping level of the n-drift region in FLI IGBT is 2 times higher than that of the conventional NPT IGBT. The higher the doping concentration, the larger the conductive n-drift region can be. Therefore, the FLI IGBT structure is available to improve the on-state voltage drop characteristic without degradation of breakdown voltage.

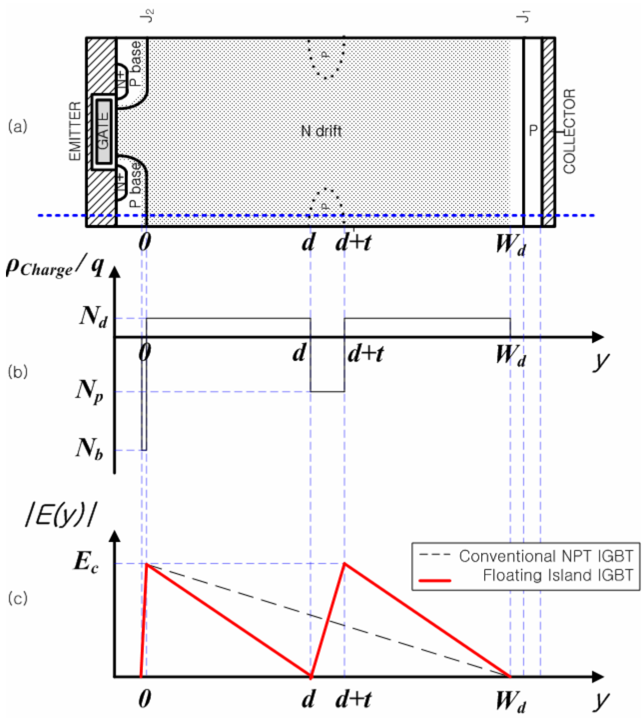


Fig. 2. Charge and electric field distribution of Floating IGBT

2.2 Device simulation

Computer simulations have been performed by using TSupreme4 and MEDICI, to confirm the improvement in on-state voltage characteristic of the suggested FLI IGBT without degradation of breakdown voltage. Also, varied design parameters were applied to confirm its dependence on electrical properties.

The conventional structure (Conventional 1200V NPT IGBT A) has been designed on the resistivity of the 60Ωcm substrate, and FLI IGBT on the 30Ωcm substrate, according to theoretical analysis. Also, the conventional structure on the 30Ωcm substrate (Conventional 1200V NPT IGBT B) was designed to be compared with the suggested FLI IGBT structure(Suggested 1200V FLI

IGBT). Other variations of parameter conditions are listed in Table 2. The result is depicted in Fig. 3.

Table 2. Variation of design parameters to compare conventional and suggested IGBT structure

Design Parameter		Conventional 1200V NPT IGBT		Suggested 1200V FLI IGBT
		A	B	
Floating Island region	W_{FLI} (um)	-		1 / 3 / 5
	Φ_{FLI}(cm^{-2})	-		5×10^{10} / 5×10^{11} / 5×10^{12} / 5×10^{13}
	d_{FLI} (um)	-		30 / 50 / 70 / 75 / 80 /85 / 90 / 110 / 130 / 150
n-drift region	thickness (um)	200		
	doping concentration (cm^{-3})	7.5×10^{13} (60Ωcm)	1.5×10^{14} (30Ωcm)	

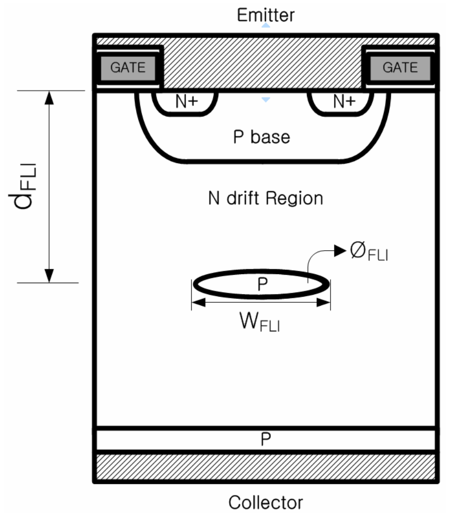
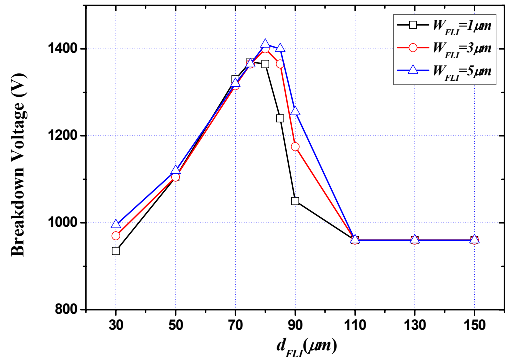


Fig. 3. Structure and simulation parameters of FLI IGBT

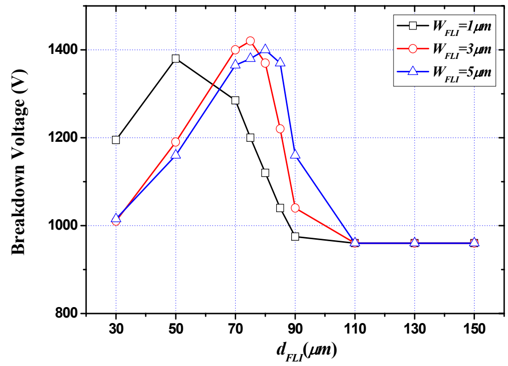
As W_{FLI} is the width of the window mask during the ion implantation process of the Floating Island. Φ_{FLI} indicates the implantation dose of the Floating Island region. The d_{FLI} value is the distance from the Floating Island center to the wafer surface, and has been divided to 20um units from 30 to 150um, and 5um units from 70 to 90um for a detailed observation. Based on Table 2, the parameters are used in the simulation to obtain the proper breakdown voltage and on-state voltage drop.

2.3 Results

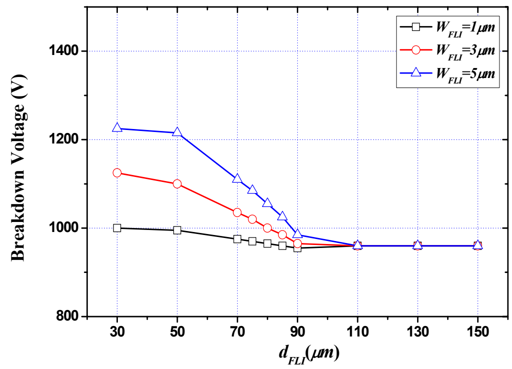
Variation of breakdown voltage characteristics with respect to variation of design parameters is shown in Fig. 4(a)~(d). Under the W_{FLI}=3um condition, the breakdown voltage with respect to the distance from the FLI center to the wafer surface d_{FLI} is plotted when the dose of the FLI region is 5×10^{13}, 5×10^{12}, 5×10^{11} and $5\times10^{10}cm^{-2}$ respectively. As shown in Fig. 4(a) and (b), the increase of



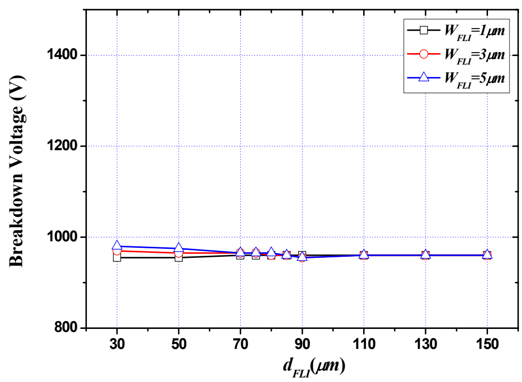
(a) $\Phi_{FLI}=5\times10^{13}$ cm^{-2}



(b) $\Phi_{FLI}=5\times10^{12}$ cm^{-2}



(c) $\Phi_{FLI}=5\times10^{11}$ cm^{-2}



(d) $\Phi_{FLI}=5\times10^{10}$ cm^{-2}

Fig. 4. Breakdown voltage and variation of parameters

d_{FLI} causes a higher breakdown voltage when the dose of the FLI region is 5×10^{13}, 5×10^{12} cm^{-2}. However, for a higher value of d_{FLI}(75um), the breakdown voltage decreases. On the contrary, in Fig. 4(c) and (d), a shorter d_{FLI} causes a higher breakdown voltage when the dose of the FLI region is 5×10^{11}, 5×10^{10} cm^{-2}. According to the result, when W_{FLI}=3um, considering that the on-state voltage drop is constant, the device is optimized to have the highest breakdown under a parameter value of $\Phi_{FLI}=5\times10^{12}$ cm^{-2}, d_{FLI}=75um.

To observe the electric field dispersion effect for comparison, the electric field distribution has been depicted in Fig. 5. Based on theoretical analysis, the highest electric field point of the optimized FLI IGBT is divided into two points on J_2 and J_{FLI}(FLI n-drift junction). Moreover, the gradient of the electric field is doubled compared with that of the conventional NPT IGBT A. In the meantime, the depletion region expansion of the suggested device is as large as that of the conventional NPT IGBT. In other words, despite the larger electric field slope, the expansion of the depletion region takes the same area. The integration value of the two structures is identical, thus they will have the same breakdown voltage characteristic.

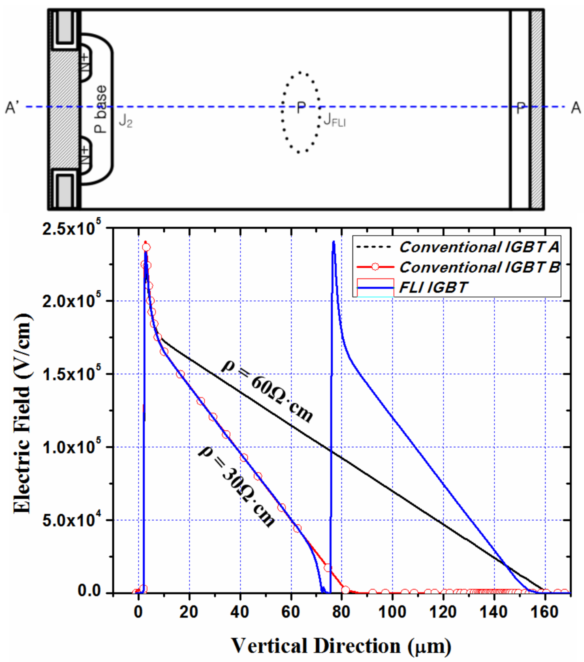


Fig. 5. Off-state electric field distribution of conventional NPT IGBT and FLI IGBT

Analyzing the on-state voltage drop, Fig. 6 exhibits the characteristics of the conventional NPT IGBT A, B and the optimized FLI IGBT. The on-state voltage drop of FLI IGBT and the conventional IGBT B was identical, as they were fabricated on the 30Ωcm resistivity wafer. They both exhibited a 2.17V drop based on the collector current of 100A/cm^2. This result constitutes a 22.5% improvement over the voltage drop of the conventional IGBT A, which was fabricated on a wafer of 60Ωcm resistivity. Table 3. shows the final comparison of three different IGBTs, proving that the optimized FLI IGBT maintains a breakdown voltage with a lower on-state voltage drop.

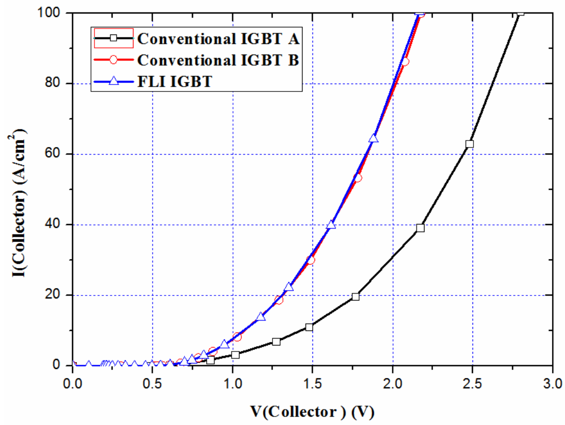


Fig. 6. I-V characteristics of conventional IGBT and FLI IGBT

Table 3. Final comparison with respect to breakdown voltage and on-state voltage drop properties between conventional NPT IGBT and FLI IGBT

Structure	N_d(cm^{-3})	Resistivity (Ω·cm)	Breakdown Voltage(V)	On-state Voltage Drop(V)
NPT IGBT A	7.5×10^{13}	60	1450	2.80
NPT IGBT B	1.5×10^{14}	30	960	2.17
FLI IGBT	1.5×10^{14}	30	1420	2.17

3. Conclusion

This paper suggested and analyzed a new FLI IGBT structure, featuring the insertion of the P Floating Island into the n-drift region, thus improving the on-state voltage drop property without degradation of breakdown voltage. This research used computer simulation to confirm the suggested structure, and analyzed its electrical properties with respect to the main design parameters. Depending on the doping level of the substrate, the Floating Island location can change. Most of the highest breakdown voltage values are obtained when FLI is located in the center. Also, to prevent punch-through breakdown, the proper dose and proper FLI width must be reserved. Considering these conditions, the final parameter s of W_{FLI}=3um, $\Phi_{FLI}=5\times10^{12}$ cm^{-3}, d_{FLI}=75um have been applied. The final optimized FLI IGBT has 1420V of breakdown voltage and 2.16V of on-state voltage drop, which is a22.5% improvement over the conventional IGBT.

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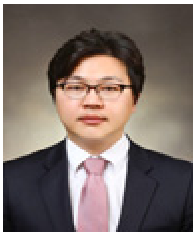

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