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Simulation-based study on the optical beam intensity dependence of the optically triggered 4H-SiC thyristors turn-on operation

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Abstract

We investigated a methodology to design the optically triggered thyristors thanks to TCAD. The simulation model accuracy, especially the holding current and the minimum incident light intensity to turn-on, were compared with experimental results. The influences of the incident light properties (wavelength and intensity) on the turn-on characteristics have been studied by simulation. We considered the wavelength dependency of the quantum efficiency, penetration depth and photon energy. The minimum intensity to turn-on significantly depends on the wavelength. This intensity becomes less than 0.003 times when the wavelength changed from 380 nm to 325 nm.

1. Introduction

SiC thyristors are dedicated to very high power applications [1]. In the recent years, Dheilly et al. reported the demonstration of direct light triggering by 360 nm wavelength UV LEDs [2]. The main advantage of the optical gate driving provides galvanic isolation simplifying device driver circuitry, and it will contribute to realize the small thyristor with high noise resistance and extremely high reliability. Compared to other power devices, designing thyristors are somewhat more challenging. The simulation model is essential to device design and circuit design. However, the triggering mechanism is strongly dependent on the structure discretization quality and designers must also face to the trade-off between the triggering sensitivity and the carrier injection between the numerous n, p layers under high dV/dt. It is difficult to calculate the device characteristics due to the abundance of number of layers. Therefore, very few articles on the simulation modeling for obtaining simulation results closer to actual measurement were published [2].

In this study, we developed a 10kV class optically triggered thyristor simulation model. We evaluated the influence of optical wavelength on the dynamical characteristics by simulation. The model accuracy was compared with experimental results.

2. Experiments

A 10kV class optical triggered thyristor was used to measure the breakover voltage, holding current and dynamical turn-on characteristics. The n, p layers were formed by epitaxial growth and the thickness of the drift-layer was set 90 μm as shown in Fig. 1. The window of anode electrode was fabricated for optical gate. We used the 365 nm wavelength UV LEDs to turn-on the thyristor. The LED gate light source has advantages in terms of the size and cost compared to UV laser.

The simulation model was made on Synopsys-TCAD (Sentaurus Device Simulator). We simulated a 2D thyristor structure and solving the model equations in cylindrical coordinates. We added the 500 kΩ series resistance between voltage source and thyristor anode electrode. The material parameters of avalanche recombination and penetration depth were taken from [3-4]. Carrier lifetime was set at 0.4 μs for electrons and 0.08 μs for holes. Some papers reported that the quantum efficiency regarding 365 nm wavelength beam radiation is small due to low photon energy [5-6]. In our simulation, the quantum efficiency varied from 1.1 % (365 nm) to 60 % (265 nm) based on the fitting to the experimental data of [5].

3. Results and Discussion

The simulated optically turn-on and turn-off characteristics are shown in fig. 2(a). The value of voltage source was swept from 0 V to 400 V with +1 V/s while a high power incident light (3800 W/cm^2, 0.1 μs) irradiated the device top optical window when the voltage reached 300 V. After the voltage reached 400 V, the voltage decreased with -1 V/s. The holding current was 0.30 mA and this result fit the experimental result well. Figure 2(b) shows the simulated lifetime dependency of the holding current. When the lifetime decreased from 0.40 to 0.50 μs, the holding current reduced by half. The lifetime is important factor to determine the

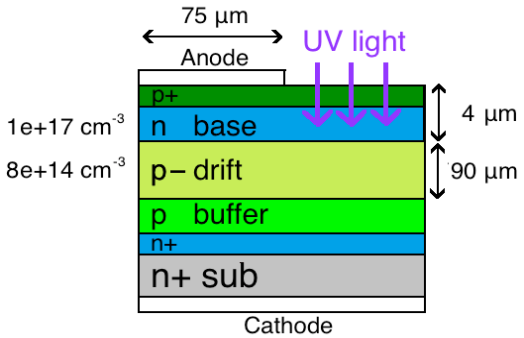

Fig. 1. Cross-section of an optical triggered thyristor for measuring the breakdown voltage and dynamical characteristics.

holding current. On the other hand, the breakover voltage did not have significant lifetime dependency in our simulation.

The minimum incident light intensity to turn-on, I_{0min} is an important factor to reduce the energy loss of the thyristor upon turn-on. Figure 3 shows I_{0min} in the range of V_{ak}=150-350 V. V_{ak} means the applied voltage at the time of the incident light irradiation. The wavelength was 365 nm and the pulse duration was set at 0.1 μs (Fig. 3(a)) and 15.4 μs (Fig. 3(b)). Experimental results with 15.4 μs pulse duration are also shown in Fig. 3(b). The simulation result at V_{ak}=300 V fits well the experimental result without any calibration of optical parameters. The multiple values of pulse duration and I_{0min} were roughly 5 W・s/m^2 at V_{ak}=300 V even if the pulse duration changed more than 100 times. This constant shows the rough relationship between pulse duration and I_{0min}. According to both of Fig. 3(a) and Fig. 3(b), I_{0min} becomes low at the high V_{ak}. Thanks to the electric field at high V_{ak}, the generated carriers are drifted to n base layer. The device then becomes more sensitive which translates into a reduction in the minimum incident light intensity required to trigger the thyristor. This explains the relationship between I_{0min} and V_{ak}.

Figure 4 shows the wavelength dependency on I_{0min}. The wavelength λ was changed from 325 to 400 nm, and a one-photon excitation phenomenon was considered in simulation model. V_{ak} is 300 V and pulse duration was 15.4 μs. I_{0min} became less than 0.003 times when λ was changed from 380 nm to 325 nm. Moreover, the thyristor did not turn-on at λ>385 nm. The experimentation with λ=400 nm violet LED shown same result as simulation -- turn-on was not occurred (not shown). These tendencies can explain by considering three phenomena.

- The quantum efficiency is set at 1.1 % for λ=365 nm and 14 % for λ=325 nm in our simulation. This wavelength dependency is the main reason of the significant I_{0min} wavelength dependency. The quantum efficiency, which is the conversion efficiency from a photon to one electron hole pair, is directly related to the quantity of photo-excited non-equilibrium carriers. If the amount of these carriers is larger than the "critical charge", the turn-on finally occurs [7].
- The penetration depth steeply decreases at short wavelength. According to [4], the penetration depth is 126 μm at λ=365 nm and 7.25 μm at λ=325 nm. However, due to the anode p+ layer and the n base layer are thin, this wavelength dependency does not affect to I_{0min}.
- When the excitation energy $E=hc/\lambda$ is smaller than bandgap (λ>385 nm), there is no way to excite the carriers even if the intensity is strong.

3. Conclusions

In this study, we developed the 10kV class optical triggered thyristor simulation model. We evaluated the influence of incident light wavelength on the dynamical characteristics by simulation. The simulated minimum incident light intensity to turn-on I_{0min} fit well the experimental results without any calibration of optical parameters. I_{0min} became less than 0.003 times when the wavelength changed from 380 nm to 325 nm. Mainly the wavelength dependency of the quantum efficiency affected to I_{0min}.

References

[1] M. E. Levinshtein, Semiconductors, 50 (2016) 408–414.
[2] N. Dheilly, et al., Electronics Letters, 48 (2011) 459-460.
[3] H. Niwa, et al., Mat. Sci. Forum. 778-780 (2014) 461-466.
[4] S. G. Sridhara, et al., Mat. Sci. and Eng. B, 61 (1999) 229-233.
[5] A. V. Sampath, et al., Electronics Letters, 49.25 (2013) 1629-1630.
[6] T. V. Blank, et al, Semicond. Sci. Technol., 20 (2005) 710-715。
[7] T. T. Mnatsakanov, et al, Semicond. Sci. Technol. 29 (2014) 055005.

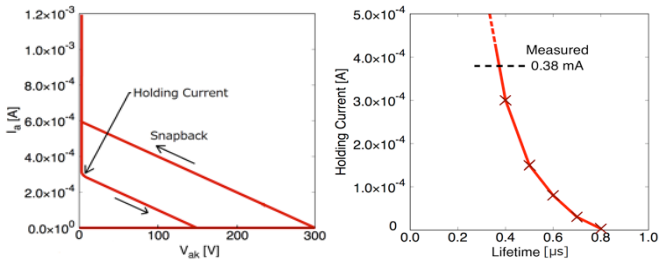

Fig. 2. Holding current simulation results. (a) Output characteristics. (b) Lifetime dependency.

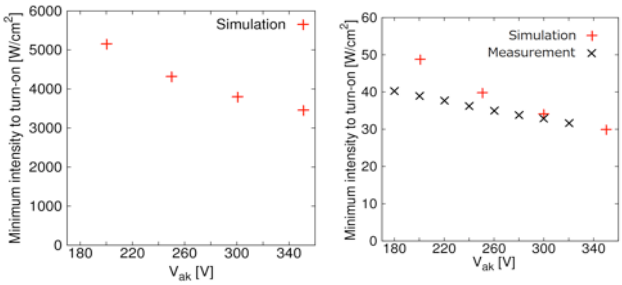

Fig. 3. Minimum incident light intensity to turn-on. The pulse duration is set at (a) 0.1 μs (b) 15.4 μs. The wavelength is 365 nm.

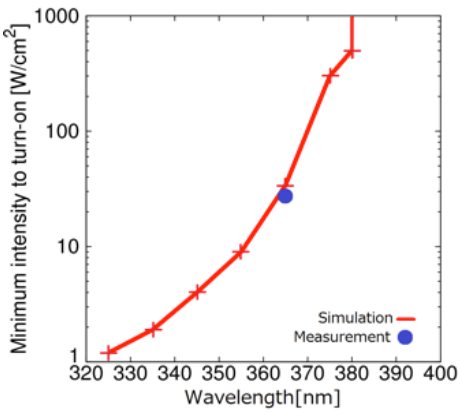

Fig. 4. Wavelength dependency on the minimum intensity to trigger the thyristor. The experimental result is shown by the blue dot. The pulse duration is set at 15.4 μs.