Injection modulation of p^+–n emitter junction in 4H–SiC light triggered thyristor by double-deck thin n-base*

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To overcome hole-injection limitation of p^+–n emitter junction in 4H–SiC light triggered thyristor, a novel high-voltage 4H–SiC light triggered thyristor with double-deck thin n-base structure is proposed and demonstrated by two-dimensional numerical simulations. In this new structure, the conventional thin n-base is split to double-deck. The hole-injection of p^+–n emitter junction is modulated by modulating the doping concentration and thickness of upper-deck thin n-base. With double-deck thin n-base, the current gain coefficient of the top pnp transistor in 4H–SiC light triggered thyristor is enhanced. As a result, the triggering light intensity and the turn-on delay time of 4H–SiC light triggered thyristor are both reduced. The simulation results show that the proposed 10-kV 4H–SiC light triggered thyristor is able to be triggered on by 500-mW/cm^2 ultraviolet light pulse. Meanwhile, the turn-on delay time of the proposed thyristor is reduced to 337 ns.

Keywords: silicon carbide, light triggered thyristor, double-deck thin n-base, injection modulation

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1. Introduction

Superior physical properties and rapid progress in growth and device technologies have made silicon carbide (SiC) well suited for high-voltage power devices.[1–3] SiC thyristors are advanced solution for increasing the power density and efficiency for high-voltage direct current electric power transmission system and power converters in smart grid.[4–6] Compared with electrically triggered thyristor (ETT), SiC light triggered thyristor (LTT) has more advantages in simplifying device driver circuitry and preventing erroneous arc firing.[7,8]

Since the first SiC LTT was triggered by a 337-nm pulse laser in 2002,[9] the studies on SiC LTTs have shown rapid development.[10–12] Because of the comparatively high ionization energy (0.19 eV) of aluminum (Al) in SiC at room temperature, the injection capacity of p^+–n emitter junction in 4H–SiC LTT is poor.[13] To switch on high voltage SiC LTTs fastly, ultraviolet (UV) laser sources are usually used to emit high intensity UV laser.[7,11,12] However, UV laser sources are cumbersome and poor efficiency. To avoid using laser sources, UV light emitting diodes (LEDs) were used to trigger SiC LTTs.[7,14] But the optical intensity of UV LEDs is low and cannot meet the requirement for fast switching of SiC LTTs. In order to overcome this problem, the amplification step is introduced and studied in 4H–SiC LTT.[15] With the amplification step, the triggering current is amplified and the minimum light intensity to turn-on SiC LTT is reduced. But hole-injection limitation of p^+–n emitter junction is still a barrier for fast switching of SiC LTT. To the best of our knowledge, there are no reports on improving hole-injection capacity of p^+–n emitter junction in SiC LTT until now.

In this paper, a novel 4H–SiC LTT with double-deck thin n-base is firstly proposed and studied. The injection modulation mechanism of p^+–n emitter junction by double-deck thin n-base is analyzed and simulated. And comparative studies of enhanced turn-on mechanism based on the novel double-deck thin n-base and the conventional thin n-base structures are carried out.

2. Device structure and mechanism

The structure schematic of a conventional 10-kV SiC LTT is shown in Fig. 1(a). Different from silicon thyristors, SiC thyristors are usually p^- blocking bases to avoid using p-type substrate. Figure 1(b) shows the structure schematic diagram of the proposed 10-kV SiC LTT. Compared with conventional SiC LTT, the thin n-base in proposed SiC LTT adopts double-deck structure. Figure 1(c) shows the doping profiles of thin n-base in both proposed thyristor and conventional thyristor. Parameter d indicates the thickness of the upper-deck in double-deck thin n-base. N_D and N_{D0} indicate the doping concentration of bottom-deck and upper-deck in proposed LTT, respectively. The doping concentration of thin n-base in conventional LTT is the same with that of bottom-deck thin n-base (N_D) in proposed LTT. The N_D in this work is fixed at 1.0×10^{17} cm^{-3}. The total thickness of thin n-base is fixed at 2.0 μm, which applies to both proposed and conventional LTTs.

Figure 2(a) shows two coupled transistor equivalent circuits for SiC LTT. In SiC LTT, the photo current forward biases the p^+–n emitter junction (J_1) and the n^+–p emitter junction

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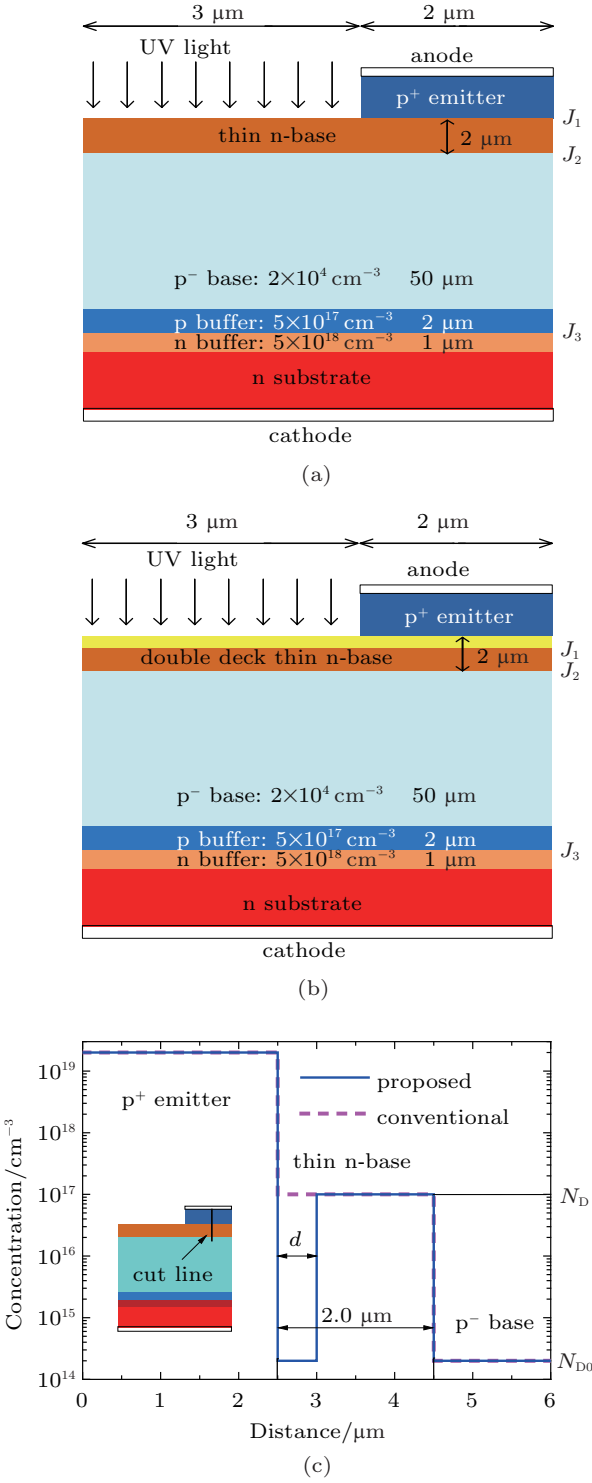


Fig. 1. (color online) Structure schematics and doping profiles of SiC LTTs (a) structure schematic diagram of conventional SiC LTT, (b) structure schematic diagram of proposed SiC LTT, and (c) the doping profiles of thin n-base in thyristors.

(J_3) to initiate the injection of holes and electrons, respectively. The injected carriers trigger a positive feedback mechanism produced by the two coupled bipolar transistors within the thyristor structure. To turn on an SiC LTT, the following condition should be satisfied,

$$\alpha_1 + \alpha_2 = \gamma_1 \alpha_{T1} + \gamma_2 \alpha_{T2} \geq 1, \quad (1)$$

where α_1 and α_2 are the current gain coefficients of the top pnp and bottom npn transistors, respectively. γ_1 and γ_2 are the injection coefficients of the top p^+–n and bottom n^+–p emitter junctions, respectively. α_{T1} and α_{T2} are the transport factors for the thin n-base and p^- blocking base, respectively. As the ionization energy of Al in 4H–SiC is high, the hole concentration in p^+ emitter region is low. As a result, the injection coefficient γ_1 of the top p^+–n emitter junction in conventional thyristor is small. The main role in turn-on mechanism of conventional SiC LTT is played by the bottom npn transistor.[16] Figure 2(b) shows the simulated *I*–*V* characteristics of top pnp transistors in proposed and conventional SiC LTTs. Compared with the top pnp transistor in conventional SiC LTT under the same optical intensity, the top pnp transistor in proposed SiC LTT shows a higher current gain. In top pnp transistor, the photo current acts as the base current. Higher optical intensity leads to higher photo current. For fixed structure parameters, the current gain difference between two transistors are fixed. Therefore, as shown in Fig. 2(b), the current density difference between two pnp transistors become bigger when under higher optical intensity. In sum, the condition to trigger positive feedback and turn on SiC LTT can be satisfied more easily with improved current gain of the top pnp transistor.

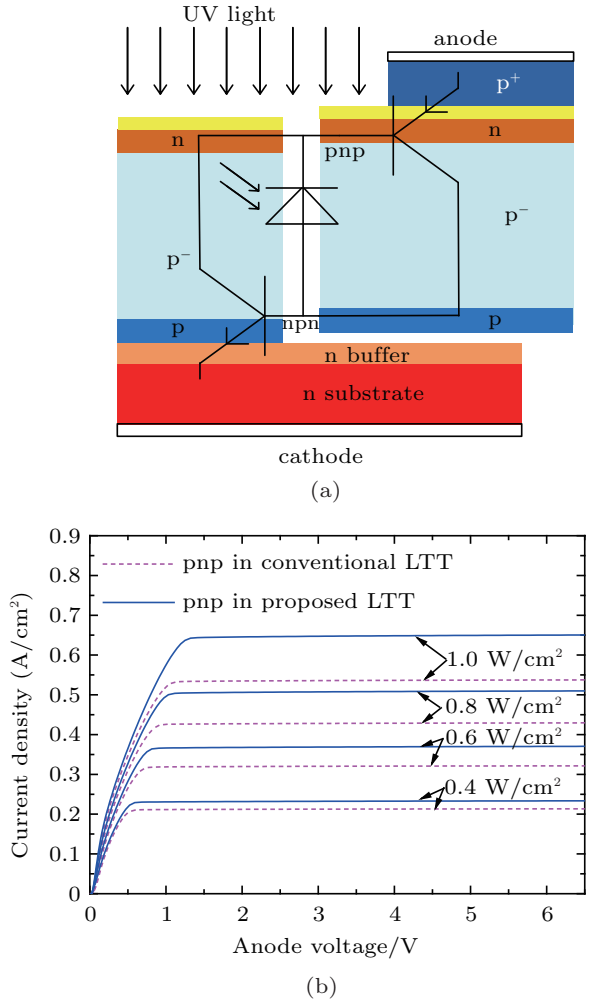


Fig. 2. (color online) (a) Structure schematic diagram of two coupled transistor equivalent circuits for SiC LTT. (b) *I*–*V* characteristics of top pnp transistors in proposed and conventional SiC LTTs.

3. Results and discussion

Simulations of 4H–SiC LTTs are carried out by Synopsys TCAD Sentaurus. The incomplete ionization of impurities is taken into account in simulation. The doping dependence of the carrier lifetimes is modeled in Sentaurus with the Scharfetter relation.[17] The temperature in the simulation is set as 300 K.

Figure 3 shows current and voltage waveforms during turn-on process of the proposed and conventional 4H–SiC LTTs. The turn-on processes of LTTs are simulated on a resistive load at a forward blocking voltage of 8500 V. The specific resistance in the resistive load is set as 90 Ω·cm^2. Monochromatic ultraviolet (UV) light with wavelength of 365 nm and intensity of 500 mW/cm^2 is used to trigger SiC LTTs. The duration time of UV light is set as 0.1 μs. The UV light pulse starts at 0 μs and ends at 0.1 μs. In keeping with the reported results,[7,12] there is a reduction of anode current density (J_A) after UV light pulse. It is because that the positive feedback is not formed during UV light duration. As current and voltage waveforms shown in Fig. 3, the proposed LTTs are all able to turn on in five microseconds, meanwhile, the conventional SiC LTT is unable to turn on in six microseconds. Which means that the formation of positive feedback in the proposed LTTs is more quickly than that in the conventional LTT.

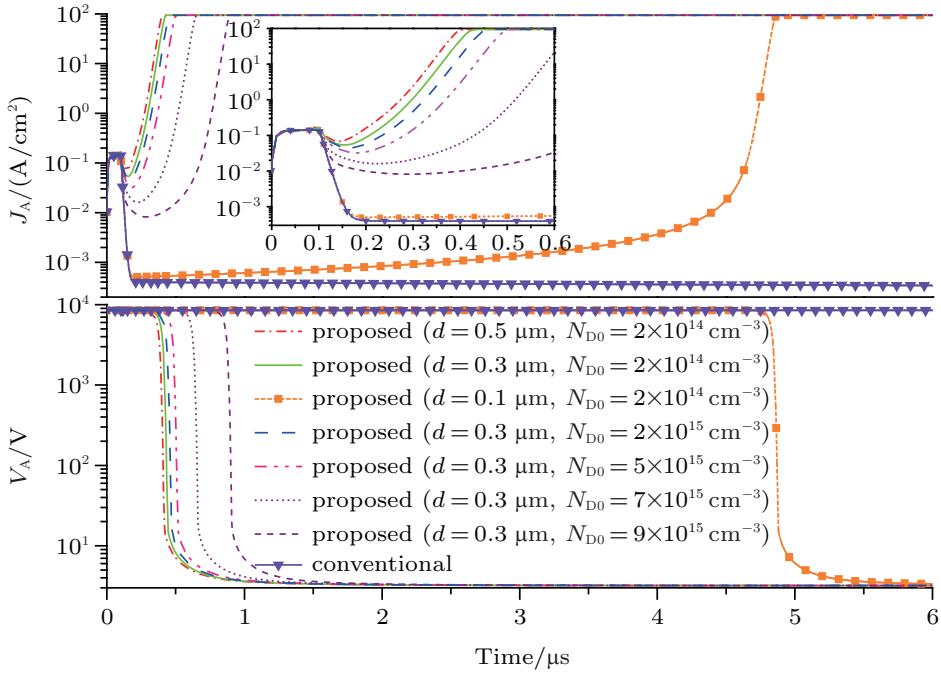


Fig. 3. (color online) Current and voltage waveforms during switching of LTTs on a resistive load.

Figure 4 shows the relationships between turn-on delay time and parameters of upper-deck thin n-base in proposed LTTs. For same d, the turn-on delay time of the proposed LTTs are reduced with decreasing of N_{D0}. For the same N_{D0}, the turn-on delay time of the proposed LTTs are reduced with increasing of d. When N_{D0} is increased, the turn-on delay difference between LTTs with different d are increased. The simulation results indicate that to obtain lower turn-on delay time, lower N_{D0} and thicker d are demand. As simulated, the turn-on delay time can be reduced to as small as 337 ns, when N_{D0} and d are 2.0×10^{14} cm^{-3} and 0.5 μm, respectively.

In order to reveal the mechanism, the hole injection and hole distributions in proposed SiC LTTs are investigated and simulated. As the structure schematic shown in Fig. 1(a), when the J_1 junction is forward biased, current flow across the junction occurs by the injection of holes into the thin n-base region as well as the injection of electrons into the p$^+$ emitter region. The injected minority carriers diffuse away from the junction, producing hole current component (J_p) and electron

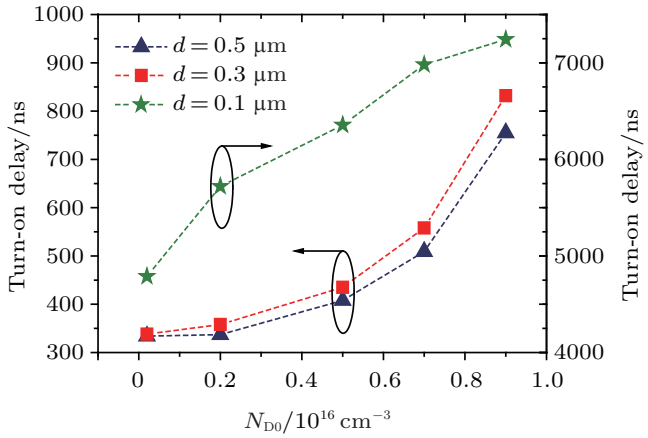


Fig. 4. (color online) Relationships between turn-on delay time and parameters of upper-deck thin n-base.

current component (J_n) for the total emitter current in top pnp transistor, respectively. In SiC LTT, the thickness of thin n-base region is smaller than the diffusion length for holes in thin n-base. The p$^+$–n emitter injection efficiency can be ob-

tained by using the electron and hole current components[18]

$$\gamma_1 = \frac{J_p}{J_n + J_p} = \frac{D_{pB} L_{nE} p_{B0}}{D_{pB} L_{nE} p_{B0} + D_{nE} W_B n_{E0}}, \quad (2)$$

where D_{pB} and D_{nE} are the diffusion coefficient for holes and electrons in the thin n-base region and p^+ emitter region, respectively. W_B and L_{nE} are the thickness of thin n-base and diffusion length for electrons in the p^+ emitter region, respectively. p_{B0} and n_{E0} are the concentration of injected holes and injected electrons at J_1 junction, respectively. The injected carrier concentrations on both sides of the J_1 junction are related to the corresponding minority carrier concentrations in equilibrium by the "law of the junction[19]"

$$p_{B0} = p_{0B} \exp\left(\frac{qV_{EB}}{kT}\right), \quad (3)$$

$$n_{E0} = n_{0E} \exp\left(\frac{qV_{EB}}{kT}\right), \quad (4)$$

where V_{EB} is the forward bias across the J_1 junction, k is the Boltzmann constant, T is the temperature, q is the charge of an electron, p_{0B} and n_{0E} are the minority carrier concentrations in equilibrium in the thin n-base and p^+ emitter region, respectively. Then, p_{B0} and n_{E0} can be expressed as

$$p_{B0} = \frac{n_{iB}^2}{\eta_D N_D} \exp\left(\frac{qV_{EB}}{kT}\right), \quad (5)$$

$$n_{E0} = \frac{n_{iE}^2}{\eta_A N_A} \exp\left(\frac{qV_{EB}}{kT}\right), \quad (6)$$

where n_{iB} and n_{iE} are the intrinsic carrier concentrations in the thin n-base and p^+ emitter region, respectively. N_D and N_A are the doping concentrations of the thin n-base and p^+ emitter region, respectively. η_D and η_A are the ionization ratios of impurities in thin n-base and p^+ emitter region, respectively. The p^+–n emitter injection efficiency can then be expressed as

$$\gamma_1 = \frac{D_{pB} L_{nE} n_{iB}^2}{D_{pB} L_{nE} n_{iB}^2 + D_{nE} W_B n_{iE}^2 \frac{\eta_D N_D}{\eta_A N_A}}. \quad (7)$$

As shown in Fig. 1(c), the double-deck structure reduces the doping concentration of the thin n-base at J_1 junction from N_D to N_{D0}. As expressed in Eq. (7), the reduction of doping concentration from N_D to N_{D0} can improve the injection efficiency of p^+–n emitter. Figure 5 shows the simulated hole density profiles of double-deck thin n-base in LTTs at 0.3 μs, 0.4 μs, 0.5 μs, and 10.0 μs, respectively. As shown in Fig. 5, the concentration of injected holes from p^+ emitter to thin n-base is increased with the decreasing of N_{D0}.

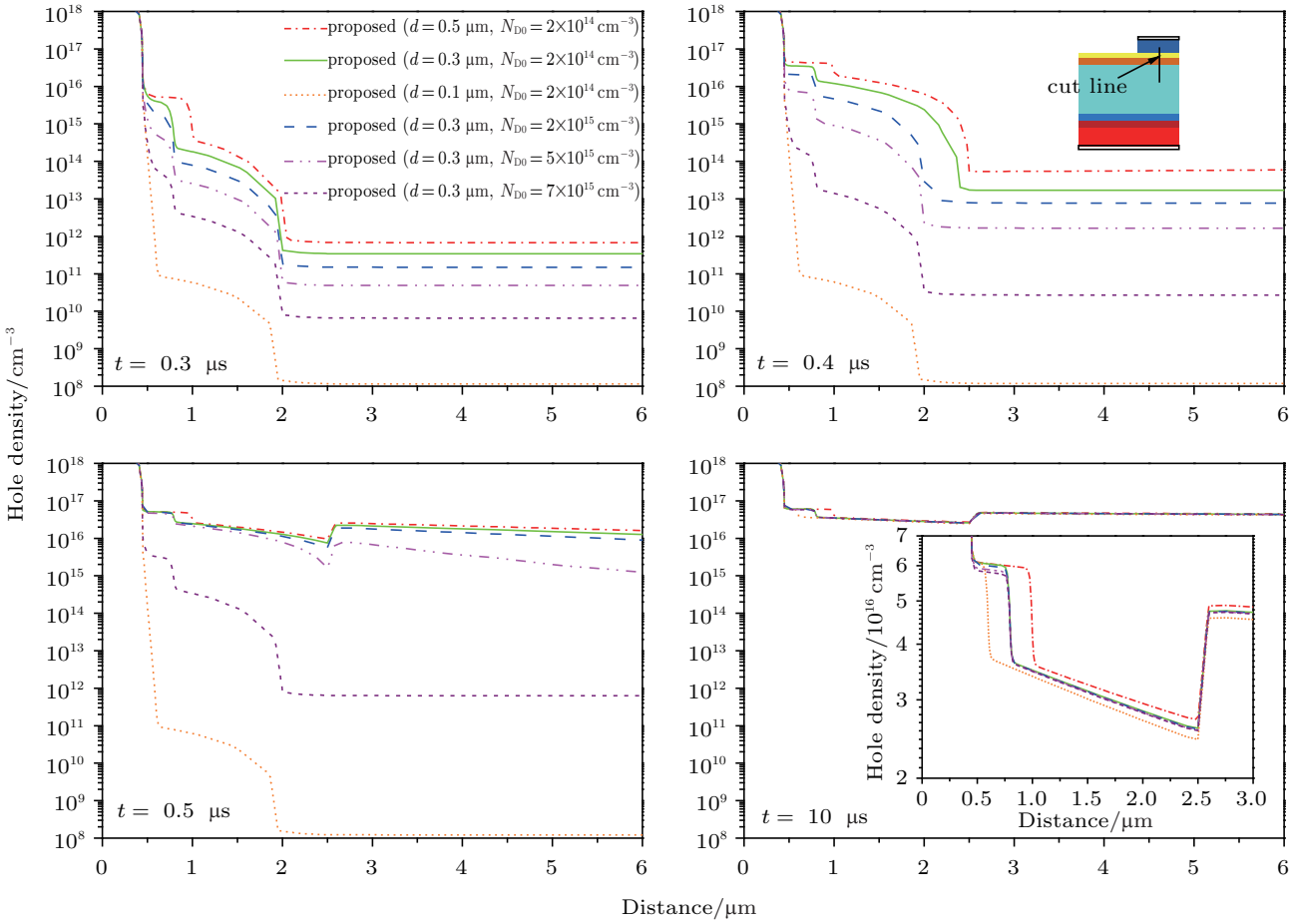


Fig. 5. (color online) Hole density profiles of thin n-base in LTTs at different time.

Because the doping concentration of bottom-deck is higher than upper-deck, there is a diffusion of electrons from bottom-deck to upper-deck at interface in the vertical direction. The flow of electrons leaves behind donor ions and induces an electric field that is in a direction to the upper-deck. The induced electric field prevent holes travelling from upper-deck to bottom-deck. As a result, the concentration of injected holes is reduced suddenly when travelling into the bottom-deck as figure 5 shows. Because the total thickness of thin n-base is fixed, the thickness of bottom-deck is reduced when increasing the thickness of upper-deck. As the minority carrier lifetime in bottom-deck is lower than that in upper-deck, thinner bottom-deck is able to reduce the minority carrier recombination in thin n-base. As shown in Fig. 5, for same N_{D0}, thicker d is able to speed up the formation of the positive feedback in SiC LTT. Furthermore, the thicker d is also able to increase the number of injected holes in thin n-base. So with the thickness of upper-deck thin n-base increased, the transport factor for the thin n-base is improved. By modulating the thickness and doping concentration of double-deck thin n-base, the injection of p^+–n emitter junction is modulated and the turn-on delay time of SiC LTT is reduced.

Figure 6 shows the forward breakdown curves of conventional LTT and proposed LTT. As can be seen from the figure, both LTTs have a breakdown voltage higher than 11.5 kV. The higher breakdown current density of the proposed LTT is caused by the modulated injection efficiency of the J_1 junction. The forward breakdown curves indicate that the proposed LTT still shows a stable forward blocking capability with improved performance.

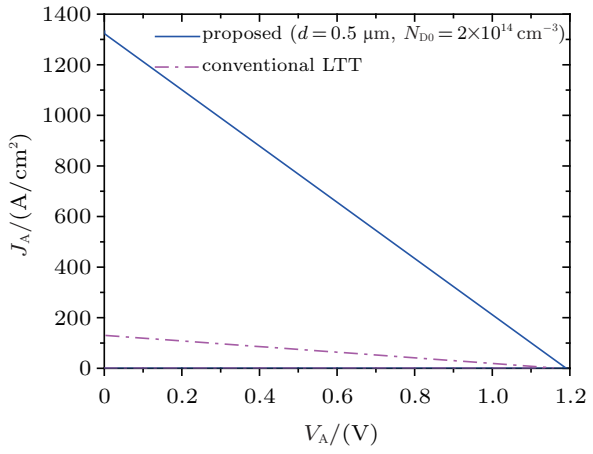


Fig. 6. (color online) Forward breakdown curves of 4H–SiC LTTs.

4. Conclusion

In conclusion, a novel high-voltage 4H–SiC LTT with double-deck thin n-base structure is proposed. The double-deck structure used in thin n-base acts as a modulation layer to improve the hole-injection efficiency of p^+–n emitter junction in SiC LTT. The theoretical results indicate that the current gain coefficient α_1 of the top pnp transistor in SiC LTT is enhanced by modulating the doping concentration and thickness of upper-deck thin n-base. The simulated turn-on and forward breakdown characteristics of the LTTs indicate that the turn-on delay time and the triggering light intensity to turn-on SiC LTT are both reduced with double-deck thin n-base. Meanwhile, the forward blocking capability of the proposed LTT keeps stable. Therefore, it is expected that the double-deck thin n-base structure can be a promising solution for fast switching of UV LEDs triggered SiC thyristor.

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