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Shortening turn-on delay of SiC light triggered thyristor by 7-shaped thin n-base doping profile*

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A new 4H–SiC light triggered thyristor (LTT) with 7-shaped thin n-base doping profile is proposed and simulated using a two-dimensional numerical method. In this new structure, the bottom region of the thin n-base has a graded doping profile to induce an accelerating electric field and compensate for the shortcoming of the double-layer thin n-base structure in transmitting injected holes. In addition, the accelerating electric field can also speed up the transmission of photon-generated carriers during light triggering. As a result, the current gain of the top pnp transistor of the SiC LTT is further increased. According to the TCAD simulations, the turn-on delay time of the SiC LTT decreases by about 91.5% compared with that of previous double-layer thin n-base SiC LTT. The minimum turn-on delay time of the SiC LTT is only 828 ns, when triggered by 100 mW/cm^2 ultraviolet light. Meanwhile, there is only a slight degradation in the forward blocking characteristic.

Keywords: silicon carbide, light triggered thyristor, 7-shaped doping profile, turn-on delay

PACS: 85.30.Rs, 85.30.De, 85.60.Bt, 02.60.Cb **DOI:** 10.1088/1674-1056/27/10/108502

1. Introduction

Thyristors have been the most powerful semiconductor switches for several decades.[1] Despite being replaced by insulated gate bipolar transistors (IGBTs) in many applications due to the latter's high switching speed and simple insulated gate control, thyristors still provide advanced solutions for increasing the power density and efficiency of high-voltage direct current electric power transmission systems.[2,3] In recent years, silicon carbide (SiC) has shown great advantages in fabricating ultra-high voltage thyristors, such as 10-kV and 22-kV emitter turn-off thyristors (ETOs).[1,4,5] With the help of the metallic oxide semiconductor field effect transistor (MOSFET), the ETO can also achieve a simple insulating gate-controlled turn-off like IGBTs.[1] However, compared with an electrical triggering mode, a light triggering mode offers many advantages in simplifying thyristor driver circuitry and preventing erroneous arc firing.[6,7] In light triggering mode, SiC light triggered thyristors (LTTs) are usually monolithically integrated with electrically triggered thyristors (ETTs) to act as pilot thyristors to trigger the main thyristor.[8–10] Therefore, the good performance of the pilot SiC thyristor is essential for the whole device.

Since the first SiC LTT was reported in 2002,[11] studies on SiC LTTs have shown rapid development.[7,12–14] To trigger high voltage SiC LTTs quickly, ultraviolet (UV) laser sources are usually used to emit high intensity UV light.[7–10,14] However, high intensity UV laser sources are cumbersome and have low efficiency. To avoid using laser sources, UV light emitting diodes (LEDs) have been used to trigger SiC LTTs.[7,12] However, the optical intensity of UV LED is too low to quickly trigger SiC LTT. This is because the comparatively high ionization energy (0.19 eV) of aluminum (Al) in SiC leads to the poor injection capacity of p^+–n emitter junctions in SiC LTT.[15] To solve this problem, in our previous work we used a double-layer thin n-base structure to enhance the hole-injection capacity.[16] With the double-layer thin n-base, the turn-on delay time (t_d) of SiC LTT can be reduced considerably when triggered using 0.5 W/cm^2 UV light.[16] However, the induced electric field between two layers prevents holes from transmitting in the thin n-base.

In this paper, a novel 7-shaped thin n-base doping profile is proposed to compensate for the shortcoming of the double-layer thin n-base structure and shorten the turn-on delay of the SiC LTT. The mechanism of the 7-shaped thin n-base doping profile in improving the performance of SiC LTT is investigated. The characteristics of the new SiC LTT with 7-shaped thin n-base doping profile, the double-layer thin n-base SiC LTT and the conventional SiC LTT are compared and analyzed.

2. Device structure and simulation setup

Structure of the conventional SiC LTT, the double-layer thin n-base SiC LTT and the new SiC LTT with 7-shaped thin n-base doping profile are schematically shown in Figs. 1(a), 1(b), and 1(c), respectively. To compensate for the shortcoming of the double-layer thin n-base structure in our previous work, the thin n-base of the SiC LTT is split into three layers, where the top layer is still lightly doped to modulate the

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hole-injection capacity of the p^+–n emitter junction, the middle layer is uniformly doped to limit the depletion width and maintain the blocking capability, and the bottom layer is gradually doped. As a result, the doping profile of the thin n-base in SiC LTT resembles the Arabic numeral "7". Because the diffusion coefficients of dopants in SiC are very small, the in situ n-type doping during chemical vapor deposition (CVD) is essential to produce SiC layers with the designed doping density and thickness. Therefore, the thin n-base should be fabricated using a modified epitaxial process.[17,18] The concentration gradient (g_D) can be controlled by quasi-continuously adjusting the mass flow rate of the N_2 during CVD growth. The detailed thin n-base doping profiles of all three SiC LTTs are shown in Fig. 1(d). The doping concentration of the top layer in the proposed thin n-base structure and the double-layer thin n-base structure are both 2.0×10^{14} cm^{-3}. L_1 and L_2 in this study are 0.3 μm and 1.0 μm, respectively.

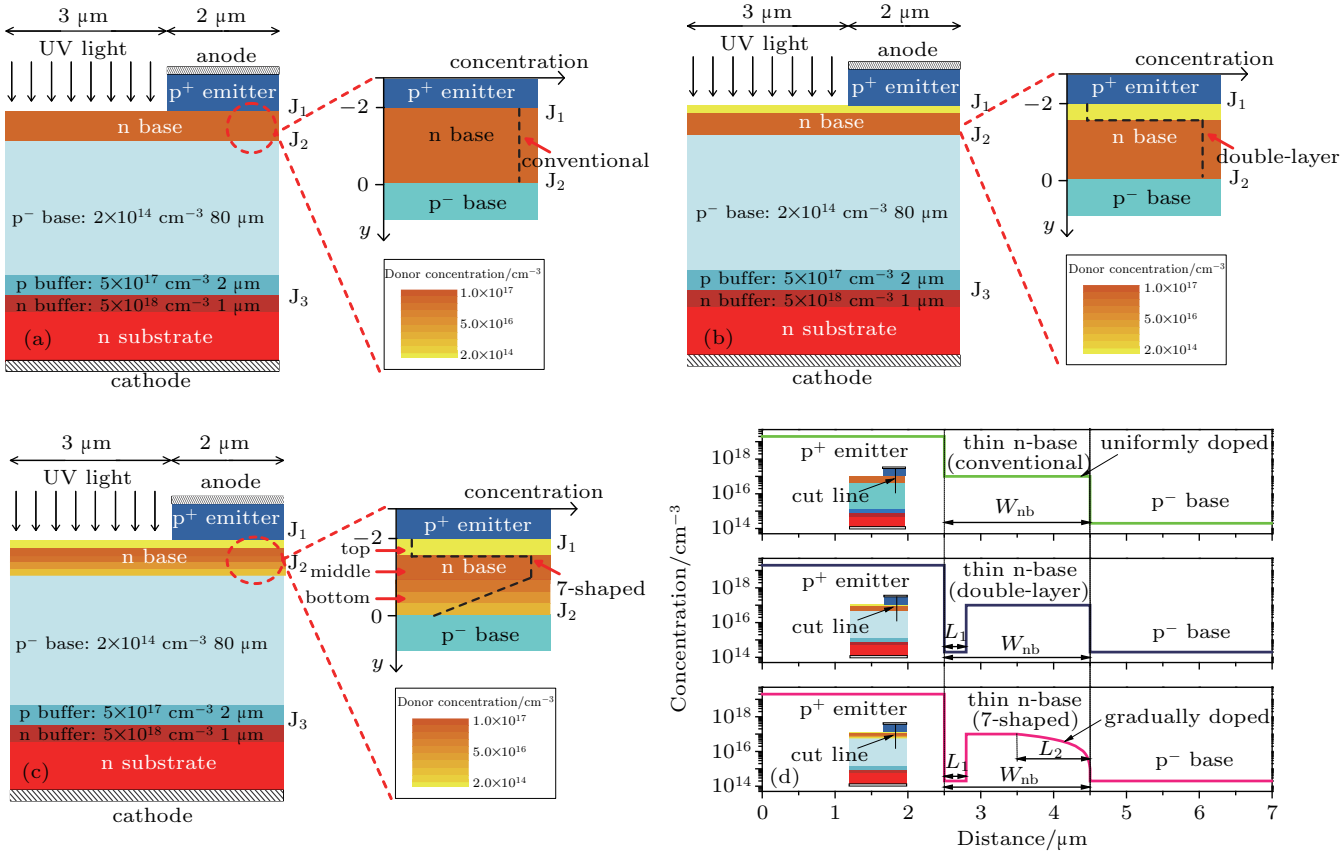


Fig. 1. (color online) Structure schematics of (a) conventional SiC LTT, (b) SiC LTT with double-layer thin n-base, (c) SiC LTT with 7-shaped thin n-base doping profile, and (d) doping profiles of all three kinds of SiC LTTs.

Table 1. Main modeling parameters for simulation of 4H–SiC LTTs.

Parameters	Value	Unit
$E_{g\ 300}$	3.26	eV
A_n	5.0×10^{-31}	cm^6/K
A_p	2.0×10^{-31}	cm^6/K
$\tau_{max,n}$	2.5×10^{-7}	s
$\tau_{max,p}$	5.0×10^{8}	s
N_{ref}	3.0×10^{17}	cm^{-3}
γ	0.3	
μ_{min1n}	40	cm^2/V·s
μ_{min2n}	950	cm^2/V·s
μ_{min1p}	53.3	cm^2/V·s
μ_{min2p}	105.4	cm^2/V·s
υ_{satn}	2.0×10^{17}	cm^2/s
υ_{satp}	2.0×10^{17}	cm^2/s
E_{AI}	0.191	eV
E_N	0.065	eV

Simulations of the devices are carried out using Synopsys TCAD Sentaurus. To obtain the closest agreement with experimental results, the simulation in our work includes the bandgap narrowing model,[19] Auger recombination model,[20] Schockley–Read–Hall (SRH) recombination model with the Scharfetter relation,[7] doping, temperature, and field-dependent mobility models,[21] incomplete ionization model,[22] avalanche generation model,[23] complex refractive index model,[22] and optical generation model.[7] The main modeling parameters for the simulation of 4H–SiC LTTs are given in Table 1. In addition, all the simulations were carried out using Fermi–Dirac statistics. The minority carrier lifetime in the p blocking base is set to be 2.0 μs and the temperature is set to be 300 K.

3. Characterization and discussion

In this section, the mechanism of the proposed structure in improving the performance of SiC LTT is investigated. The comparative study between the new SiC LTT, the double-layer thin n-base SiC LTT, and the conventional SiC LTT is conducted.

3.1. Formation of accelerating electric field

For the proposed doping profile, the impurity concentration of the bottom gradually doped layer can be expressed as

$$N(y)=\begin{cases} N_{\mathrm{D0}}-g_{\mathrm{D}}y, & (0\geq y\geq -1),\\ N_{\mathrm{D0}}+\delta\cdot g_{\mathrm{D}}, & (-1\geq y\geq -1.7), \end{cases} \tag{1}$$

where N_{D0} is the lowest impurity concentration at the interface of the J_2 junction, g_{D} is the net impurity concentration gradient in the gradually doped region, and δ is the constant with a value of 1.0 μm. In the blocking state, the electric field and potential in the space charge region of the gradually doped region can be determined from a one-dimensional Poisson equation

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}y^2}=-\frac{\mathrm{d}E(y)}{\mathrm{d}y}=-\frac{\rho(y)}{\varepsilon_{\mathrm{s}}}=-\frac{q\cdot\eta\cdot N(y)}{\varepsilon_{\mathrm{s}}}, \tag{2}$$

where ε_{s} is the dielectric coefficient for 4H–SiC, and η is the ionization ratio of donor in thin n-base. As the electric field must go to zero at the edge of the depletion region, the electric field distribution in the depletion region of the proposed thin n-base can be written as

$$E_{\mathrm{G}}(y)=\begin{cases} \dfrac{q\eta N_{\mathrm{D0}}}{\varepsilon_{\mathrm{s}}}(y+W_{\mathrm{NG}})-\dfrac{q\eta g_{\mathrm{D}}}{2\varepsilon_{\mathrm{s}}}(y^2-W_{\mathrm{NG}}^2), & (W_{\mathrm{NG}}\leq 1.0\ \mu\mathrm{m}),\\ \dfrac{q\eta N_{\mathrm{D0}}}{\varepsilon_{\mathrm{s}}}(y+C)-\dfrac{q\eta g_{\mathrm{D}}}{2\varepsilon_{\mathrm{s}}}(y^2-C^2)+\dfrac{q\eta(N_{\mathrm{D0}}+\delta g_{\mathrm{D}})}{\varepsilon_{\mathrm{s}}}(W_{\mathrm{NG}}-C), & (W_{\mathrm{NG}}>1.0\ \mu\mathrm{m},\ y\geq -1.0),\\ \dfrac{q\eta(N_{\mathrm{D0}}+\delta g_{\mathrm{D}})}{\varepsilon_{\mathrm{s}}}(W_{\mathrm{NG}}+y), & (W_{\mathrm{NG}}>1.0\ \mu\mathrm{m},\ y<-1.0), \end{cases} \tag{3}$$

where W_{NG} is the depletion width in the proposed thin n-base and C is the constant with a value of 1.0 μm. When the depletion width is shorter than the gradually doped width, the gradually doped region in the thin n-base is partially depleted. In the unexhausted region, there is a diffusion of electrons from the region of high concentration to the region of low concentration in the vertical direction. The flow of electrons leaves behind donor ions, and thus inducing an electric field (E_{i}) that is in the direction pointing to the J_2 junction. The E_{i} can then be given by

$$E_{\mathrm{i}}(y)=-\frac{kT}{q}\cdot\frac{g_{\mathrm{D}}}{N_{\mathrm{D}}(y)},\quad(-1.0\leq y\leq -W_{\mathrm{NG}}), \tag{4}$$

where k is the Boltzmann constant, T is the temperature, q is the charge of an electron, g_{D} is the net impurity concentration gradient, and $N_{\mathrm{D}}(y)$ is the doping concentration.

According to Eqs. (3) and (4), the electric field distributions are calculated. Figure 2 shows the calculated electric field distributions of thin n-base structures with constant doping profile and proposed graded doping profile in the SiC LTTs under different bias voltages based on coordinates established in Figs. 1(a) and 1(c). The impurity concentration and the g_{D} used in the electric field calculation refer to Fig. 1(d). The impurity concentration of the middle layer and the g_{D} of the bottom layer in the thin n-base with 7-shaped doping profile are 1.0×10^{17} cm^{-3} and 9.9×10^{20} cm^{-4}, respectively. The impurity concentration in the thin n-base with a constant doping profile is 1.0×10^{17} cm^{-3}. As shown in Fig. 2, the depletion width in the gradually doped thin n-base is wider than that of the uniformly doped thin n-base under high and low blocking voltage conditions. Furthermore, an electric field along the whole gradually doped region is induced under a low blocking voltage.

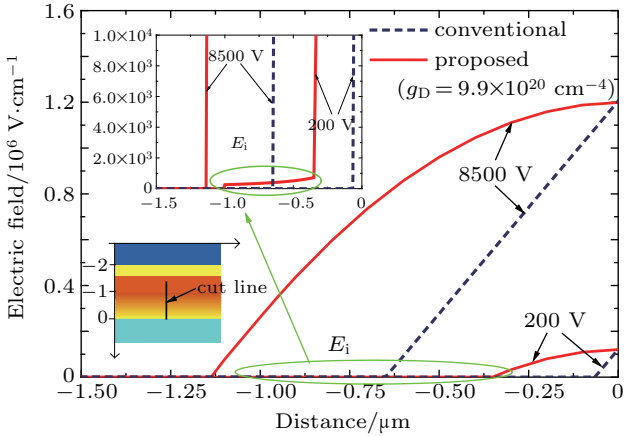


Fig. 2. (color online) Calculated electric field distributions of gradually and uniformly doped thin n-base structures in SiC LTTs under different bias voltages.

Due to the presence of the induced electric field in thin n-base, the holes travel through this region at a drift velocity given by

$$v_{\mathrm{p}}(y)=\mu_{\mathrm{p}}E_{\mathrm{i}}(y)=-\frac{kT}{q}\cdot\frac{g_{\mathrm{D}}}{N_{\mathrm{d}}(y)}\cdot\mu_{\mathrm{p}}, \tag{5}$$

where μ_{p} is the hole mobility in the gradually doped region. The induced electric field acts as an accelerating electric field. As a result, the hole transmission mechanism in the thin n-base is changed from only diffusion to the combination of drift and

diffusion. The hole transport efficiency of the thin n-base with the proposed doping profile is enhanced.

3.2. Enhanced current gain of top pnp transistor

Figure 3(a) shows a two-coupled transistor equivalent circuit for SiC LTT. To turn on an SiC LTT, positive feedback should be formed between two transistors. Because of the poor injection capacity of the p^+–n emitter junction, the current gain of the top pnp transistor is low. As a result, the establishing of the positive feedback in the conventional SiC LTT needs a comparatively long time.

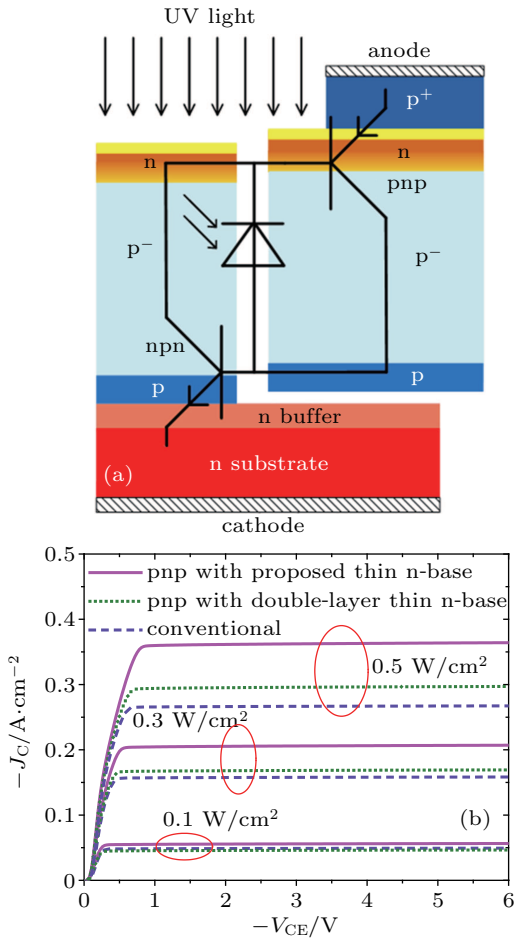


Fig. 3. (color online) (a) Structure schematics of two-coupled transistor equivalent circuit for SiC LTTs, and (b) output characteristics of the top pnp transistors in different LTTs.

The simulated output characteristics of the top pnp transistors in different SiC LTTs are shown in Fig. 3(b). The pnp transistors with the proposed thin n-base structure and double-layer thin n-base structure show the enhanced current gains at 0.5 W/cm^2 and 0.3 W/cm^2, respectively. Furthermore, the pnp transistor with the proposed thin n-base structure shows a higher current gain than the pnp transistor with the double-layer thin n-base structure. When reducing light intensity to 0.1 W/cm^2, the pnp transistor of the double-layer thin n-base SiC LTT does not show any obvious enhanced current gain any more. This is because the electric field induced by the two layers prevents the hole from transmitting and has a greater influence on device performance at lower light intensity. In the pnp transistor with the proposed thin n-base structure, the gradually doped region can compensate for the shortcomings of the double-layer structure, and still shows an enhanced current gain under 0.1-W/cm^2 UV light triggering.

3.3. Characteristics of SiC LTTs

The turn-on performances of the SiC LTTs are simulated on a resistive load. The resistance in the resistive load is set to be 90 Ω·cm^2. Monochromatic UV light with a wavelength of 365 nm, an intensity of 100 mW/cm^2, and a duration of 0.4 μs is used to trigger the SiC LTTs.

Figure 4 shows the simulated current and voltage waveforms of the SiC LTTs in the turn-on processes. The inset shows the resistive load circuit. Like previously reported results, the anode current first decreases and then increases, because the positive feedback is not formed in UV light duration.[7,14] The proposed and the double-layer thin n-base SiC LTTs are triggered on by 100 mW/cm^2 UV light, however, the conventional SiC LTT cannot be triggered on in 14 μs. The current and voltage waveforms show that the proposed and double-layer thin n-base structure can both reduce the turn-on delay time (t_d) of SiC LTTs, with the proposed SiC LTT showing a shorter t_d than the double-layer thin n-base SiC LTT. When g_D of the gradually doped layer is zero, the proposed thin n-base structure degenerates into a double-layer structure. With g_D increasing from zero to 9.0×10^{20} cm^{-4}, the t_d of the proposed SiC LTT clearly decreases from 10.18 μs to 863 ns, corresponding to a reduction of about 91.52%. With g_D continuously increasing from 9.0×10^{20} cm^{-4} to 9.9×10^{20} cm^{-4}, the t_d decreases from 863 ns to 828 ns. The t_d decreases slowly and the decrease ratio is only 0.34%.

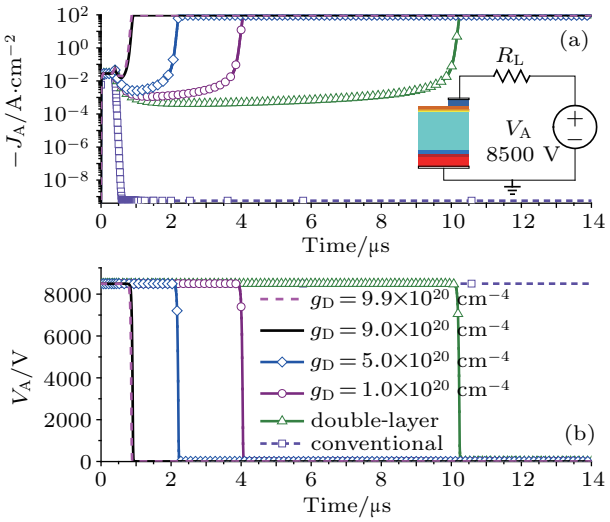


Fig. 4. (color online) Turn-on waveforms of the SiC LTTs on a resistive load in turn-on processes: (a) current waveforms and (b) voltage waveforms.

The simulated hole density profile of the proposed and double-layer thin n-base SiC LTTs are shown in Fig. 5. The g_D of the proposed SiC LTT is 9.0×10^{20} cm^{-4}. Because the top layers of the thin n-base have the same doping profile, the hole densities in the top layers are the same between the two SiC LTTs.

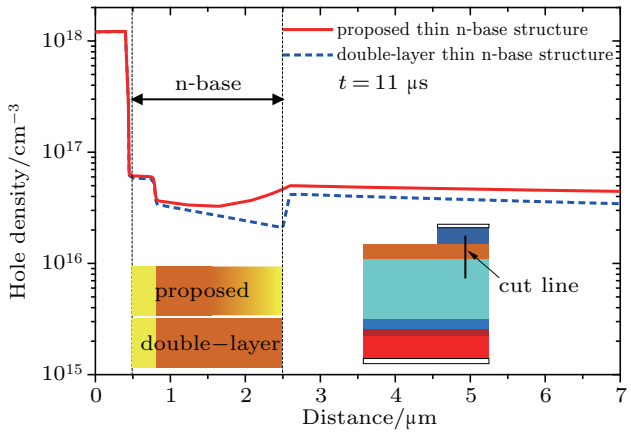


Fig. 5. (color online) Hole density profiles of SiC LTTs with different thin n-base structures at 11 μs.

Furthermore, as in the case of the double-layer thin n-base SiC LTT, there is also an induced electric field preventing injected holes from transmitting through the thin n-base in the proposed SiC LTT. As a result, the hole density profiles decrease suddenly at the interface between the top layer and middle layer. The decrease of the injected hole density degrades the performance of the double-layer thin n-base SiC LTT, especially under low triggering light intensity. Fortunately, the bottom region in the proposed thin n-base is gradually doped. The bottom gradually doped region can induce an electric field to speed up the injected holes' transmission. With the existence of the accelerating electric field, the hole transmission mechanism is changed from only diffusion to the combination of drift and diffusion in the proposed SiC LTT. Therefore, the hole density profile increases at the bottom layer of the thin n-base in the proposed SiC LTT. Comparing the proposed SiC LTT with the double-layer thin n-base SiC LTT, the injected holes in the p blocking base increase from 4.18×10^{16} cm^{-3} to 5.0×10^{16} cm^{-3} when the g_D of the proposed SiC LTT is 9.0×10^{20} cm^{-4}. It means that an approximately 19.6% increment of injected hole density can be achieved by changing the double-layer thin n-base structure to the proposed thin n-base structure.

Figure 6 shows the forward breakdown curves of SiC LTTs with the proposed thin n-base and double-layer thin n-base structure. The forward breakdown curves indicate that the LTTs with the proposed thin n-base structure still show the stable forward blocking capability with improved turn-on performance. Furthermore, with the increasing of g_D, the breakdown voltage of the device decreases slightly.

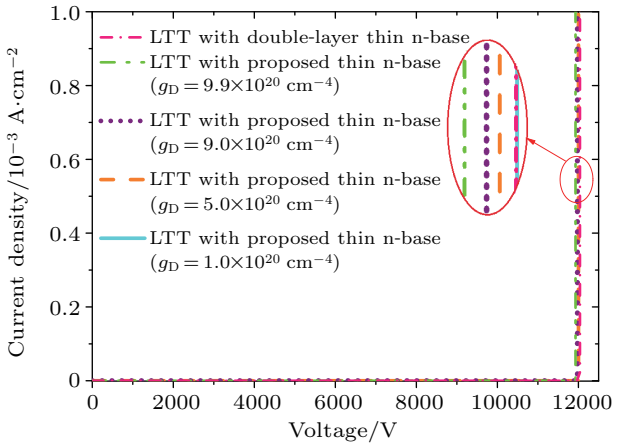


Fig. 6. (color online) Forward breakdown curves of 4H–SiC LTTs.

4. Conclusions

In this paper, a new thin n-base structure with 7-shaped doping profile is proposed and investigated to compensate for the shortcoming of the previous double-layer thin n-base structure in transmitting injected holes. The novel thin n-base structure in the proposed SiC LTT can induce an accelerating electric field in the thin n-base to speed up the transmission of photon-generated carriers and injected holes. As a result, the current gain of the top pnp transistor in the SiC LTT further increases compared with that in the double-layer thin n-base SiC LTT. According to the TCAD simulations, by changing the double-layer thin n-base structure to the proposed structure, the turn-on delay time is reduced by $\sim 91.5\%$ with a slight degradation in forward blocking characteristic. In addition, the injected holes in the p blocking base increase from 4.18×10^{16} cm^{-3} to 5.0×10^{16} cm^{-3} when the g_D of the proposed SiC LTT is 9.0×10^{20} cm^{-4}. In conclusion, it is expected that the 7-shaped thin n-base doping profile can be a promising solution for the fast switching of UV LED triggered SiC thyristors.

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