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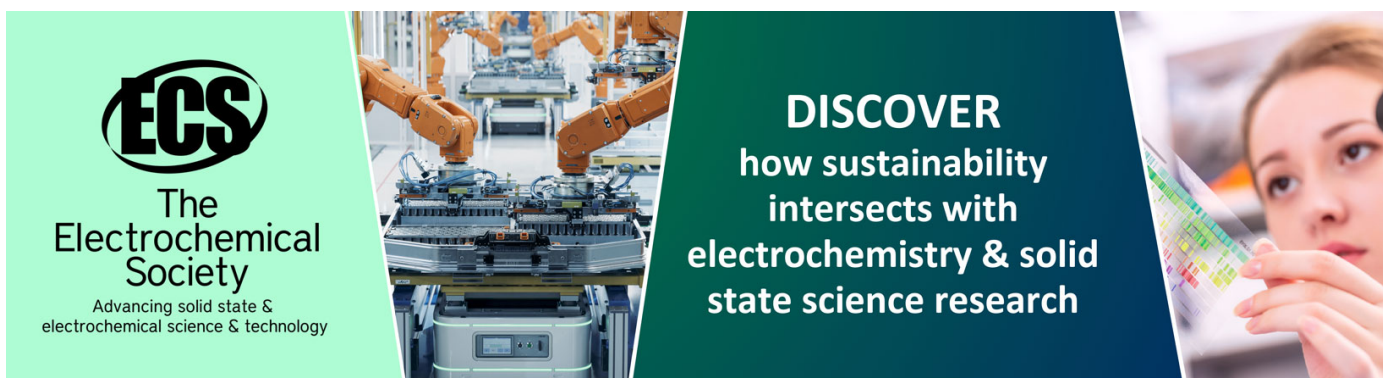
A new rear-illuminated vanadium-compensated 4H-SiC photoconductive switches with AlN anti-reflection coating

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A new rear-illuminated vanadium-compensated 4H-SiC photoconductive switches with AlN anti-reflection coating

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Abstract. This paper presents a new rear-triggered vanadium-compensated 4H silicon carbide (4H-SiC) photoconductive semiconductor switch (PCSS) with aluminum nitride (AlN) anti-reflection coating on the back of PCSS device. Characteristics of PCSS are investigated by using semiconductor device simulation software Silvaco-TCAD. The switch substrates were doped with vanadium to make the substrates highly insulated. The on-state performance of the photoconductive switch was tested under pulsed light conditions with a wavelength of 532 nm and an optical power density of 6.8 MW/cm² at a bias voltage of 2 kV. And the bias voltage was increased from 0 V to 10 kV in the absence of light trigger conditions, and its off-state characteristics were tested. Results show that the electric field strength between electrodes can be reduced by using rear-triggered structure, the switch breakdown voltage is over 80 kV DC, the maximum transient current is about 137 A, and the tail current almost disappears when the pulse light is turned off. In addition, the breakdown voltage of the rear-triggered PCSS to be higher than that of the front-triggered one. After adding AlN anti-reflection coating on the switch, the maximum transient of the switch and the optical utilization efficiency of laser energy are significantly improved, the maximum transient current of the switch was greatly improved from 137 A to 150 A, which was increased by about 9.4 %. In addition, the effects of substrate thickness and optical power density on the switching performance were evaluated.

1. Introduction

During the past decades, traditional gas and mechanical switches are difficult to meet the needs of pulse power systems development, photoconductive semiconductor switch (PCSS) has broad application prospects in the field of pulse radar and pulse power systems, due to their low jitter, high power, high repetition rate, current rising speed, narrow pulse width, high peak current withstand capability, low loss, and long life and other advantages [1-3]. For the limitations of Si and GaAs in PCSS applications, according to previous research results, SiC has better performance than Si and GaAs semiconductor materials widely used in photoconductive semiconductor switch [4-6]. 4H-SiC is currently experiencing an increasing demand for power device applications due to its wider bandgap (3.26 eV), larger critical electric field (2.2 MV/cm), higher thermal conductivity (4.9 W/cm·K) and faster saturation drift velocity (2.2×10^7 cm/s $\perp$ c, 0.33×10^7 cm/s $\parallel$ c) compared with Si and GaAs [7-9]. These characteristics determine the application fields of materials.

In 1972, S.Jayaraman and C.H.Lee of the University of Maryland found that the response time of a photo-semiconductor irradiated with a light pulse on the order of ps was also on the order of ps, laying an important foundation for the development of photoconductive switches [10]. Three years later, the American Bell Laboratory made a silicon photoconductive switch [11]. In 1977, C.H. Lee et al. found



that photoconductive switches of GaAs perform better than silicon photoconductive switches [12]. K.Zhu reported a 4H-SiC photoconductive switch with n^+ -GaN subcontact and Si_3N_4 passivation in 2007, the passivation layer of Si_3N_4 plays an important role in suppressing leakage current and improving breakdown voltage, but n^+ -GaN epitaxial layer reduces contact resistance [12]. In 2012, Cameron Hettler et al. also proposed a coplanar type photoconductive switch with a ring-shaped electrode, the switching devices used high-purity semi-insulating 4H-SiC substrate and trigger from the back of the switch by using a 532 nm laser, and the breakdown voltage of the devices was increase to 50 kV [13].

Although the growth technology of SiC semiconductor materials continues to maturity, nitrogen and boron impurities are inevitably mixed in the crystal growth process, and the insulating properties of the prepared SiC materials possess poor performance due to the presence of impurities [14,15]. In order to obtain better insulation properties of SiC, during the growth process to compensate. In 4H-SiC material, vanadium (V) as an electrically amphoteric impurity that vanadium produces a deep acceptor level that binds free electrons on the impurity level of the shallow donor, and vanadium produces a deep donor level near the center of the forbidden band, compensating for excess holes on the shallow acceptor impurity level [16,17].

For the photoconductive switches with the plane transverse structure, surface flashover easily occurs, and the voltage withstanding performance of the switch devices decreases [3],[13],[15]. In order to prevent untimely breakdown of the front-triggered PCSS due to surface flashover and high current density, rear-triggered radial structure with AlN anti-reflection coating on the back of PCSS device was adopted in paper [12],[15], schematic of device as shown in Figure 1. In terms of withstand voltage and peak photocurrent, this structure has obvious advantages. By means of semiconductor device simulation software Silvaco-TCAD effect of AlN anti-reflection coating on the performance of 4H-SiC PCSS characteristics has been investigated. Furthermore, the 4H SiC PCSS was comprehensively evaluated by changing the optical power density and the substrate thickness respectively. The results show that this structure has higher voltage withstand and peak photocurrent than that of the front-triggered one. In particular, the breakdown voltage of the devices and the optical utilization efficiency are significantly improved in this rear-triggered vanadium-compensated 4H-SiC PCSS with AlN anti-reflection coating.

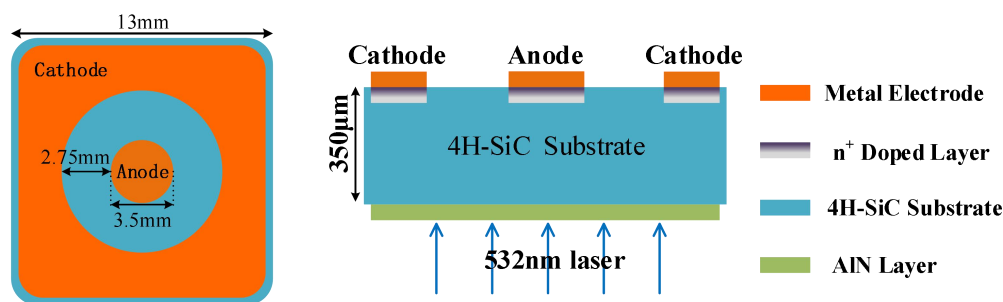


Figure 1. Schematic of device in the top view and longitudinal section.

2. Materials and Simulation Details

The rear-triggered structure 4H-SiC PCSS used in experiment is shown in Figure 1. The PCSS model was established by Silvaco-TCAD. The size of switch substrate is 13 mm $\times$ 13 mm, thickness is 350 μm and the gap between the two electrodes is 2.75 mm. The phosphorus ion was implantation on the substrate under the electrode, the surface of phosphorus concentration is $1 \times 10^{20} \text{ cm}^{-3}$, with depth of 300 nm. The aim was to improve the ohmic contact of the substrate and the electrode. By using an optical pulse with 532 nm and 7 ns FWHM, the 4H-SiC PCSS was tested On-State performance.

At present, it is difficult to achieve high purity 4H-SiC crystals, because the growth process is imperfect, impurities will inevitably be introduced in the growth process. The main impurities are boron (B) and nitrogen (N), which are the main acceptor and donor impurities in 4H-SiC crystals,

respectively. In the switch model, the concentration of unintentionally doped nitrogen is set to $1 \times 10^{15} \text{ cm}^{-3}$, and that of boron to $1 \times 10^{14} \text{ cm}^{-3}$. Due to the substrate impurity ionization, the switch will produce larger dark current leakage. Doping vanadium impurities in the 4H-SiC substrate can make the substrate have higher resistance, vanadium can be used as amphoteric impurity is introduced to compensate for B acceptor and N donor impurities in 4H-SiC substrate. The forbidden band width of 4H-SiC material is 3.26 eV, the acceptor level of vanadium is 0.76 eV below the conduction band, and the donor level is 1.62 eV on the valence band [18].

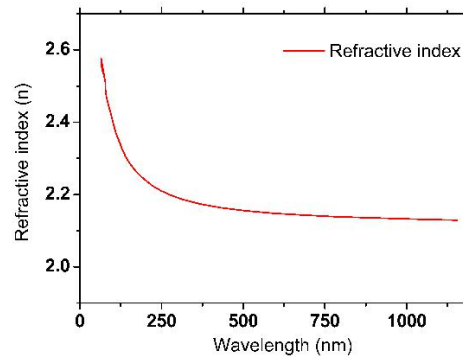


Figure 2. Refraction index of AlN film. The refractive index of AlN (2.15) is less than 4H-SiC (2.65) at 532 wavelength..

Figure 2 shows the refraction index of AlN film, which has a refractive index of $n = 2.15$ at a wavelength of 532 nm. AlN film have excellent optical properties, the optical transmittance rate can reach more than 90 % at around 532 nm. It has high thermal conductivity [2.85 W/(cm·K)], high resistivity ($>10^{13} \Omega \cdot \text{cm}$), low dielectric constant (8.5), high mechanical strength and thermal expansion coefficient ($10^{-6}/\text{K}$) similar to 4H-SiC [19-22]. The PCSS generates a large amount of heat during operation, and it is very important to be able to release the heat effectively. AlN has high thermal conductivity and resistivity, and is often used as a passivation layer for high-power devices to improve device stability. Material parameters of 4H-SiC and AlN are shown in Table 1.

Table 1. Material parameters of 4H-SiC and AlN

Name of Parameters	4H-SiC	AlN
Band gap width (eV)	3.23	6.2
Dielectric constant (ϵ_r)	9.7	8.5
resistivity ($\Omega \cdot \text{cm}$)	10^{12}	10^{13}
Thermal conductivity (W/cm·k)	4.9	2.85
Coefficient of thermal expansion ($10^{-6}/\text{k}$)	4.7	4.5
The lattice constants A	3.073	3.110

Both AlN and 4H-SiC crystals are wurtzite structure, and their lattice constants and thermal expansion coefficients are very close. The lattice mismatch between the AlN film and the 4H-SiC substrate is calculated by:

$$\delta = \frac{a_s - a_e}{a_s} \quad (1)$$

where a_s is the lattice constant of the 4H-SiC substrate, a_e is the lattice constant of the AlN film, the calculated lattice mismatch is only 1 % [23-25]. Thermal expansion coefficients of AlN and 4H-

SiC are close, so the AlN film is not easily peeled off even at high temperatures. The AlN film has high transmittance near 532 nm wavelength, and its refractive index is much less than that of the 4H-SiC substrate, it can be used as an anti-reflection coating for the switches, the most suitable thickness of anti-reflection coating can be calculated by the principle of thin film interference:

$$\lambda_1 = \frac{\lambda_0 n_0}{n_1} \quad (2)$$

$$2d = (2k+1) \frac{\lambda_1}{2} \quad (3)$$

where λ_0 and λ_1 are the wavelength of light in air and film respectively, and the refractive index of air and film respectively, and d is the thickness of AlN anti-reflection coating. The wavelength of optical pulse is 532 nm in this paper, so the thickness of the AlN anti-reflection coating is selected to be 308 nm. The detailed parameters of the simulation of 4H-SiC PCSS are shown in Table 2.

Table 2. The simulation parameters of PCSS

Name of Parameters	Values
4H-SiC band gap(eV)	3.26
4H-SiC saturated electron velocity(10^7 cm/s)	2.0
4H-SiC electron mobility($\text{cm}^2/\text{V}\cdot\text{s}$)	900
4H-SiC hole mobility($\text{cm}^2/\text{V}\cdot\text{s}$)	120
4H-SiC substrate thickness(μm)	350
AlN band gap(eV)	6.2
AlN anti-reflection coating thickness(nm)	308
Bias voltage(kV)	2
Optical power density(MW/cm^2)	6.8
The optical pulse wavelength(nm)	532

3. Results and Discussion

The transient current, dark resistivity and breakdown voltage are important parameters for measuring the performance of PCSS. The 4H-SiC PCSSs were tested in both the Off-State and On-State. The breakdown voltage of the switch in Off-State were measured DC I-V curves. The photoconductivity of the devices was measured using the setup illustrated in Fig. 3. Among them, V_{DC} source is DC high voltage source, R_m is current limiting resistance, R_L is load resistance, C_L is charging capacitor and CVR is current detecting resistance [3], [16].

3.1. AlN anti-reflection coating Performance

The operation of the PCSS require high energy pulsed light irradiation. Adding an AlN an-tireflective film to the photoconductive window of the PCSS can reduce the reflection loss of the pulsed light, thus reducing the requirement for the excitation energy of the pulsed light. In order to evaluate the performance of antireflective coating, we have established two samples models with and without anti-reflection coating, the performance of two samples was tested in 2 kV bias. When the optical power density higher than 6 MW/cm^2 , the switch resistance is getting to be stable, and the tested maximum transient currents at the density of 6.8 MW/cm^2 are 150 A and 137 A, respectively. Figure 4 shows that the transient current characteristics of the two samples are with and without anti-reflection coating, respectively. With AlN anti-reflection coating, the switch devices have higher transient current than those without anti-reflection coating. The maximum transient current of the switch is greatly improved

from 137 to 150 A by incorporation of AlN anti-reflection coating, which is increased by about 9.4%. This results indicates that AlN has the great potential in these photoconductive switches devices.

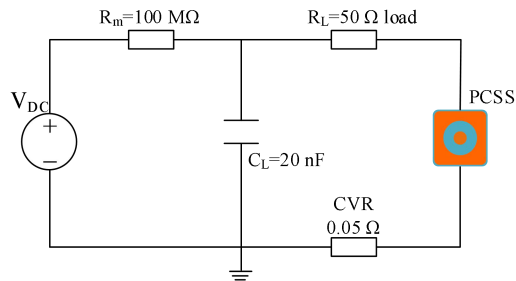


Figure 3. Circuit schematic of the On-State test setup circuit.

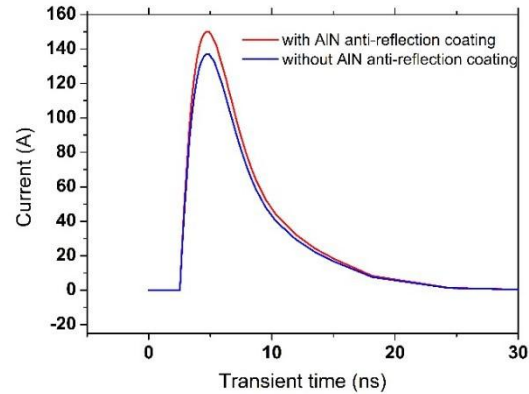


Figure 4. The transient current characteristics of PCSS with and without anti-reflection coating.

3.2. On-State characteristics of PCSS

The device versions were evaluated over varying laser energy, varying applied voltage, and varying substrate thickness. All On-State data presented was obtained using 532 nm laser illumination. We have established three different substrate thickness models of 250, 350 and 450 μm for simulation experiments, they are Sample 1, Sample 2 and Sample 3, respectively.

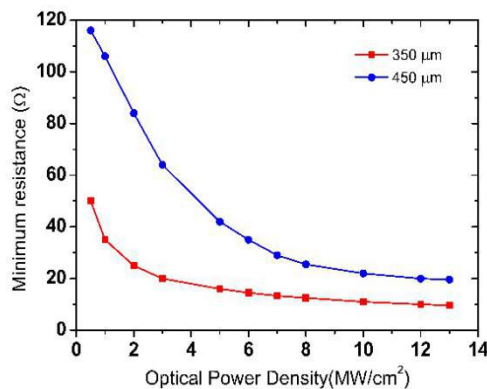


Figure 5. Minimum resistance versus optical power density.

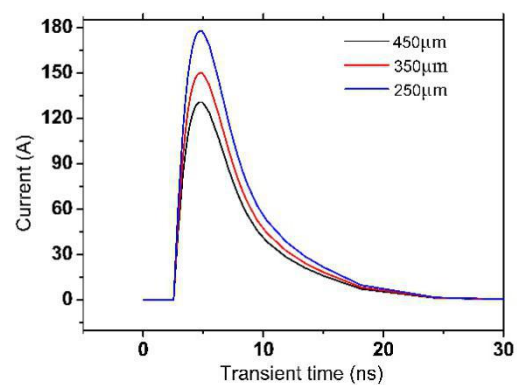


Figure 6. The transient characteristics of PCSS with different substrate thicknesses.

The minimum On-State resistance of sample 2 and sample 3 were tested in 2 kV bias. The relationship between the minimum on-resistance and the optical power density is shown in Figure 5. We found to the On-State resistance vary with substrate thickness that with the increase of the thickness of the substrate, the laser energy reaching the vicinity of the electrode decreases, the number of photo-generated carriers decreases. And the transport length of photogenerated carriers increases correspondingly, which increases the collision probability among carriers, phonons and defects. As a result, the resistance of PCSS increased. The PCSS exhibited a decrease in resistance with increasing laser energy over the range of 0–6 MW/cm^2 . When the optical power density higher than 6 MW/cm^2 ,

the resistance is getting to be stable, and the minimum On-State resistance of PCSS with a substrate thickness of 350 μm achieved 14.5 Ω .

As shown in Fig 6, the transient characteristics of PCSS with different substrate thicknesses are depicted. When the optical power density is constant, the carrier generation rate in the PCSS device remains unchanged. With the increase of carrier transmission distance, the number of carrier reach to top contact of the device decreases, so the peak current becomes smaller. The photoconductive switching transient current decreases with the increase of the substrate thickness at the other conditions remain unchanged.

3.3. Off-State characteristics of PCSS

The breakdown voltage of the 4H-SiC photoconductive switch determines the application field of the device. The high withstand voltage characteristic can save the cost of the overvoltage protection circuit for the power electronic system and improve the stability of the device.

In order to study the effect of the 4H-SiC substrate thickness on PCSSs performance, we have established three different substrate thickness models of 250, 350 and 450 μm for simulation experiments. The other conditions are the same, the breakdown voltages of the three sample were tested with the conditions of the bias voltage from 0 to 80 kV, the test results are shown in Figure 7. It can be seen from the figure that the breakdown voltage is 75 kV when the substrate thickness is 250 μm , the breakdown voltage is 80 kV when the thickness is 350 μm . Moreover, the breakdown voltage of 450 μm substrate thickness is higher than that of 350 μm substrate thickness. According to the results, the breakdown voltage of the PCSS increases with the increase of substrate thickness.

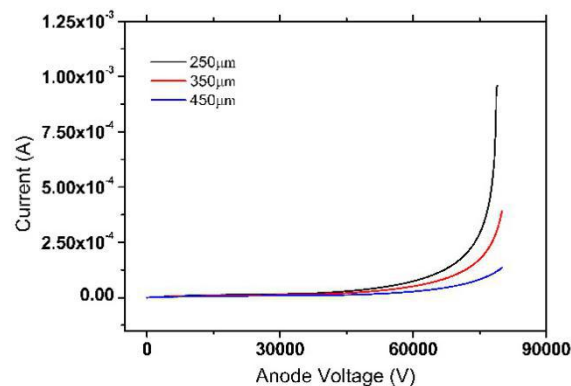


Figure 7. The breakdown voltage of the three sample.

The surface breakdown of the electrode coplanar PCSS is mainly due to surface flash breakdown. When the voltage is applied across the switch, the local field strength near the junction of the electrode, crystal and environmental interface is increased, and it is easy to generate electrons here, the electron collision causes new electrons to be generated on the crystal surface, the carriers continue to collide with the substrate under the electric field to continue to generate new electrons, a large number of electrons form a penetrating conductive channel, the surface flashover forms and on the surface leave unrecoverable traces and eventually cause the switch to fail.

4. Conclusions

In summary, a new rear-triggered vanadium-compensated 4H silicon carbide (4H-SiC) photoconductive semiconductor switch (PCSS) with aluminum nitride (AlN) anti-reflection coating was studied by Silvaco-TCAD semiconductor simulation software. AlN was deposited on 4H-SiC substrate for anti-reflection of 4H-SiC photoconductive switching devices, the rear-illuminated structure switch was triggered using an optical pulse of 532 nm wavelength, with optical power density of 6.8 MW/cm², the maximum transient current of the switch was greatly improved from 137 A to 150 A at 2 kV bias, which was increased by about 9.4 %. In addition, the switch parameters of the back-illuminated structure are evaluated for different device thickness and optical power density in this paper. The 4H-SiC PCSS current decreases with the increase of substrate thickness at the other conditions remain unchanged, while the breakdown voltage of the switch increases with the increase of substrate thickness. When the PCSS substrate thickness is 350 μm , the breakdown voltage is 80 kV, which is higher than the previously reported 4H-SiC PCSS structure.

Acknowledgments

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