The Effect of SiC-MOSFET Characteristics on the Performance of Dielectric Barrier Discharge Plasma Actuators with Two-Stroke Charge Cycle Operation

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Abstract: The low-voltage operation of a dielectric-barrier-discharge (DBD) plasma actuator with a simple electric circuit has the potential to put it into industrial applications. However, there is an issue that the efficiency of the low-voltage operated DBD plasma actuator is lower than that of the high-voltage operated one. In this study, the characteristics of silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs), which are used in the electric circuit, are investigated with a focus on the on-state resistance. The on-state resistance of the SiC-MOSFET affects the rise time of the applied voltage in our experimental condition. The energy consumption by applying a pulse voltage to the DBD plasma actuator increases with increasing the on-state resistance. Flow visualization with particle image velocimetry measurement reveals that a DBD plasma actuator with the SiC-MOSFET whose on-state resistance is the lowest induces the highest velocity of the ionic wind. Also, low on-state resistance is preferable in terms of the thrust-to-power ratio. These findings contribute to the development of an optimal power supply for DBD plasma actuators for industrial applications.

Keywords: dielectric barrier discharge plasma actuator; electrohydrodynamics; SiC MOSFET; low-voltage operation

1. Introduction

Dielectric barrier discharge (DBD) plasma actuators have been extensively studied as novel airflow control devices without any moving parts [1]. A commonly used DBD plasma actuator consists of two electrodes and a dielectric material: one electrode is exposed to air, and the other is covered with the dielectric. The electrodes are arranged in an asymmetric manner along with the dielectric surface. Surface discharge is formed when a high alternative-current (AC) voltage is applied to the electrodes, inducing ionic wind due to electrohydrodynamic (EHD) force generated by the surface discharge [2]. The DBD plasma actuators actively control the airflow using the ionic wind (e.g., controlling the separating flow around an airfoil [3], turbulent boundary-layer drag reduction [4], and enhancing mixing of the jet flow [5]). Owing to the advantages of their simple structure and the fast response over conventional flow control devices, the DBD plasma actuators have been developed for practical applications [6]. Previous studies have been devoted to the development of a small high-voltage AC power supply for the implementation of DBD plasma actuators on small aircraft in recent years [7,8].

However, several challenges remain for the industrial applications of DBD plasma actuators. Firstly, the induced flow velocity is not enough to control the flow field at high speed; therefore, a lot of studies have been devoted to improving the performance of the DBD plasma actuators [9,10]. Although the previous studies investigated key factors to enhance the induced flow velocity both experimentally [11,12] and numerically [13–15], a drastic improvement is still required.
Secondly, even if a relatively strong ionic wind can be induced, a high-voltage power supply is needed (a voltage of 70 kV_{peak−peak} is required to generate the thrust of 200 mN/m [16]). The necessity of the high-voltage power supply may hinder the practical applications of DBD plasma actuators for electric cars and aircraft in view of the weight of the power supply and ensuring electrical insulation. To overcome this problem, we proposed a highly integrated DBD plasma actuator, which consists of several modules of a three-electrode DBD plasma actuator [17]. The flow velocity induced by the proposed DBD plasma actuator increases when increasing the number of modules without increasing the amplitude of the applied voltage. In addition, the proposed DBD plasma actuator generates mutually enhanced the EHD force by designing the applied voltage waveform and electrode configuration while the conventional DBD plasma actuator with multi-electrode fails to generate unidirectional ionic wind due to a harmful cross-talk phenomenon [18]. We demonstrated that the maximum velocity of 4.5 m/s was obtained by using the multi-stage plasma actuator with only an amplitude of 1500 V, indicating that the same magnitude of ionic wind velocity induced by a high-voltage operated DBD plasma actuator is achievable [19]. However, a study for the optimization of the low-voltage operated DBD plasma actuators in terms of the EHD force generation has never been performed. Especially, since the applied voltage waveform strongly affects the performance of the DBD plasma actuators [11], the effect of the voltage waveform on the induced flow velocity should be clarified. The investigation of the effect of the applied voltage waveform for the proposed DBD plasma actuator provides new insight into the performance improvement of DBD plasma actuators because the process of the EHD force generated by the proposed DBD plasma actuator, which employs a waveform of direct current (DC) biased repetitive pulses, is different from the conventional DBD plasma actuator, which usually employs a sinusoidal waveform [20].

In view of the practical application, a power supply to drive surface DBDs is required. Solid state switches including metal-oxide-semiconductor field-effect transistors (MOSFETs) are widely used to generate a high voltage pulse [21,22]. A previous study developed a nanosecond pulse generator using semiconductor opening switches and insulated gate bipolar transistors [23]. In another study, the DBD plasma actuator was operated by direct switching of high DC voltage to generate a pulsed-DC waveform [24]. The direct switching of a high-DC voltage can easily generate repetitive pulses. The performance of solid-state switches affects the generated pulse waveform and the electrical power that the power supply consumes. Therefore, it is important to improve the performance of the pulse generator as long as the pulse waveform has an important role in the electrical and mechanical characteristics of the DBD plasma actuators.

In this study, the effects of silicon carbide (SiC) MOSFET characteristics on the performance of the DBD plasma actuator driven by the DC-biased repetitive pulses are explored. We especially focus on the effect of the on-state resistance of the SiC-MOSFET on the pulse waveform (rise and fall times). The electrical and mechanical characteristics of the DBD plasma actuator are investigated through the voltage and current waveform observation, and the visualization of the induced ionic wind. In Section 2, the experimental setup including the electrical circuit with employed SiC-MOSFETs and the flow visualization methodology is described. We discuss the effect of the characteristics of the SiC-MOSFETs on the electrical and mechanical characteristics of the DBD plasma actuator in Section 3.

2. Experimental Setup

Figure 1 shows the schematic diagram of the electrical circuit for driving the DBD plasma actuator with the two-stroke charge cycle operation. This electrical circuit consists of a DC power supply (Matsusada Precision HAR-2P-150, Tokyo, Japan), two solid-state switches (SiC-MOSFETs, Infineon Technologies, Inc., Neubiberg, Germany), and a resistor. The resistor (10 Ω) was inserted between the DC power supply and the high-side switch to adjust the applied voltage waveform [25]. In this study, a half-bridge circuit was employed to drive the DBD plasma actuator. The applied voltage rapidly decreases to 0 V by opening
the high-side switch and closing the low-side switch. By contrast, the applied voltage rapidly increases to the DC voltage by closing the high-side switch and opening the low-side switch. DC-biased repetitive pulses were formed by repeating these processes. The applied voltage and discharge current were measured by using a high-voltage (IWATSU SS-0171R, TEquipment, Inc. Long Branch, NJ, USA) and a current probe (Pearson model 2877, Pearson Electronics, Inc. Palo Alto, CA, USA), respectively. A detailed description of forming the DC-biased repetitive pulses is found in Ref. [15]. An eight-stage DBD plasma actuator was used in this study. The width of the exposed and covered electrodes were 1.5 mm and 2.5 mm, respectively. A copper tape was employed as an electrode. A 0.05 mm-thick polyimide tape was used as a dielectric layer.

![Figure 1. Schematic diagram of the electrical circuit for driving the DBD plasma actuator. Electrode arrangement and size of the DBD plasma actuator are also described.](image)

To investigate the effect of the characteristics of the SiC-MOSFET, three different SiC-MOSFETs were employed as the switch of the half-bridge circuit (Figure 2). The key parameters for the DBD characteristics include drain-to-source voltage, drain current, and on-state resistance. The drain-to-source voltage and drain current determine the withstanding voltage and the allowable current that flows the SiC-MOSFET due to DBDs. All SiC-MOSFETs employed in this study satisfy these limits. The on-state resistance is the resistance between the drain and the source of a SiC-MOSFET during on-state and is an inherent characteristic of the SiC-MOSFET. The on-state resistance affects the time constant for the charging and discharging phases. Therefore, the fall and rise times of the applied voltage depend on the on-state resistance. The fall and rise times strongly affect the characteristics of atmospheric pressure discharge [26]. The typical value of the on-state resistance of MOSFET A (ROHM SCT2H12NZ, ROHM Co., Ltd., Kyoto, Japan) is 1.15 Ω. MOSFET B (Wolfspeed C2M1000170D, Cree, Inc., Durham, NC, USA) has a similar on-state resistance (1.0 Ω). The on-state resistance of MOSFET C (Wolfspeed C2M0080170D, Cree, Inc., Durham, NC, USA) is the lowest of the three SiC-MOSFETs (80 mΩ). This study employed a half-bridge circuit, which consists of two SiC-MOSFETs, to operate the DBD plasma actuator. Hence, two SiC-MOSFETs were used for each case (MOSFET A, B, or C). The SiC-MOSFETs were driven by a gate driver (Nihon Pulse Industry GDUSC30, Nihon Pulse Industry, Co., Ltd., Tokyo, Japan). The gate signal was formed by using a function generator (NF WF1974, NF Corporation, Yokohama, Japan).

To characterize the flow field induced by the DBD plasma actuator in quiescent air, particle image velocimetry (PIV) was performed. The PIV system consists of a pulse laser system (Photonics Industries DM-60-532, Photonics Industries International Inc., Ronkonkoma, NY, USA) and a high-speed camera (Phantom VEO1310, Phantom, Inc., Wayne, NJ, USA). The sampling frequency of the images for PIV analysis was set to 10 kHz. The image for PIV analysis was recorded with a resolution of 1280 pixels \times 360 pixels. In this study, the single-pixel ensemble correlation method was employed rather than
the spatial correlation method to obtain a time-averaged flow field because the single-ensemble correlation method provides a higher resolution than that obtained using the spatial correlation method \[27,28\]. The cross-correlation coefficient for the single-pixel ensemble correlation \( R \) was obtained as follows:

\[
R(s) = \frac{\sum_{k=1}^{N} \left\{ I_1^{(k)}(x) - \bar{T}_1 \right\} \left\{ I_2^{(k)}(x+s) - \bar{T}_2 \right\}}{\left( \sum_{k=1}^{N} I_1^{(k)}(x) - \bar{T}_1 \right)^2 \left( \sum_{k=1}^{N} I_2^{(k)}(x+s) - \bar{T}_2 \right)^2}, \tag{1}
\]

where superscript \((k)\) denotes the \(k\)-th image pair, \(s\) is the displacement of the image pattern, 
\(N\) is the number of image pairs, \(I_1\) and \(I_2\) are the intensity of the pixels for the first and second image of the pair, respectively, and \(x\) is the position vector. The values of \(\bar{T}_1\) and \(\bar{T}_2\) were obtained by

\[
\bar{T}_1 = \frac{1}{N} \sum_{k=1}^{N} I_1^{(k)}(x), \tag{2}
\]

\[
\bar{T}_2 = \frac{1}{N} \sum_{k=1}^{N} I_2^{(k)}(x+s). \tag{3}
\]

The time-averaged flow field was obtained from 10,000 image pairs, which were taken after the induced flow reached a quasi-steady state. The detailed setup of the PIV analysis is found in Ref. \[29\].

3. Result and Discussion

Figure 3a shows the time histories of the applied voltage for different SiC-MOSFETs. The DC voltage was set to 1200 V. At \(t = 0\) µs, the low-side switch was closed to connect the exposed electrode to the ground. To eliminate shoot-through currents, a dead time of 1 µs was provided. At \(t = 1\) µs, the low-side switch was closed (and the high-side switch was opened) so that the DC voltage could be applied to the exposed electrode. The fall and rise times for different SiC-MOSFETs are summarized in Table 1. The fall time was shorter than the rise time regardless of the SiC-MOSFETs since a resistor was inserted between the DC power supply and the high-side switch. Although the fall time seems to become short with decreasing the on-state resistance, the variation of the fall time was 3 ns. By contrast, the rise time decreased from 90 ns to 66 ns by decreasing the on-state resistance from 1150 mΩ to 80 mΩ. A previous study reported that the peak value of the discharge current increased by decreasing the rise time in a streamer discharge observed in a point-to-plane configuration \[26\]. Figure 3b shows the time histories of the discharge current for different SiC-MOSFETs. Negative and positive polarity pulses, which were observed at \(t = 0\) µs and \(t = 1\) µs, corresponded to pulsed discharges during the voltage falling and rising phases, respectively. The peak values of the negative and positive pulses are summarized in Table 2. During the voltage falling phase, the amplitude of the current pulse increased
by decreasing the fall time of the applied voltage as reported in a previous study [26]. In addition, during the voltage-rising phase, MOSFET C, whose on-state resistance was the lowest, indicated the largest peak value of the current pulse. A previous work showed that the reduction of the on-state resistance of the SiC-MOSFET shortens the rise times of the applied voltage [30]. Hence, the reduction of the on-state resistance increases the discharge current owing to the shortening of the rise time of the applied voltage in the DBD plasma actuator. Consequently, we conclude that the on-state resistance of the MOSFET plays an important role in the applied voltage and discharge current waveforms. Note that in this study, the effect of the impedance change of the DBD plasma actuator is not considered. The impedance of the DBD plasma actuator could change due to the degradation of the exposed electrode and the dielectric layer. The dielectric material used in this study is a polyimide tape whose dielectric loss tangent is 0.002 (1 kHz). Although the degradation time scale depends on the dielectric material, a previous study reported that the exposed electrode and the dielectric layer are degraded when the operation time of the DBD plasma actuator reaches tens of hours, leading to a change in the impedance of the DBD plasma actuator [31,32].

Figure 3. Time histories of (a) applied voltage and (b) discharge current for different SiC-MOSFETs.
Table 1. Fall and rise times for different SiC-MOSFETs.

| MOSFET | Fall time | Rise time |
|--------|-----------|-----------|
| A      | 33 ns     | 90 ns     |
| B      | 30 ns     | 86 ns     |
| C      | 31 ns     | 66 ns     |

Table 2. Peak values of the discharge current during the falling and rising phases for different SiC-MOSFETs.

| MOSFET | Current peak of negative pulse | Current peak of positive pulse |
|--------|--------------------------------|-------------------------------|
| A      | −4.01 A                        | 1.88 A                        |
| B      | −5.03 A                        | 1.77 A                        |
| C      | −4.65 A                        | 2.26 A                        |

Figure 4 shows the pulse energy density as a function of the voltage of the DC power supply for different SiC-MOSFETs. The pulse energy density was calculated as the integral of the instantaneous power [33]. The energy increased by increasing the DC voltage and decreasing the on-state resistance of the SiC-MOSFET. Hence, the difference in the SiC-MOSFET affects the electrical characteristics of the DBD plasma actuator even when the same electrical circuit for operating the DBD plasma actuator is employed.

Figure 5 shows the time-averaged spatial distributions of the $x$-component of the velocity induced by a DBD plasma actuator with different SiC-MOSFETs when the DC voltage and repetitive pulse frequency were set to 1200 V and 150 kHz, respectively. The origin of the coordinate was set at the downstream edge of the exposed electrode of the first-stage module. A wall jet parallel to the wall was induced downstream regardless of the types of SiC-MOSFETs. However, in the cases of using MOSFET A and B, the DBD plasma actuator failed to induce successive acceleration of the wall jet due to weak discharge (i.e., lack of the amount of the charged particles to be accelerated). The peak velocity of approximately 2 m/s was obtained in the cases of the MOSFET A and B. In addition, the induced flow fields with MOSFET A and B showed almost the same spatial distribution. By contrast, the flow field induced by the DBD plasma actuator with MOSFET C indicated that a successively accelerated wall jet, and a peak velocity of approximately 3 m/s, were
achieved. This result suggests that the characteristics of the SiC-MOSFET have an important role in the formation of the wall jet. The applied voltage waveform depends on the types of the SiC-MOSFET (mainly the on-state resistance). Especially, we can conclude that the applied voltage waveform during the voltage rising phase strongly affects the induced flow field based on the result that MOSFET C showed a different voltage waveform during this phase compared to the waveforms of MOSFET A and B.

Figure 5. Time-averaged spatial distributions of the x-component of the velocity induced by a DBD plasma actuator with different SiC-MOSFETs.

To discuss the induced flow field in detail, the effect of the repetitive pulse frequency was investigated. Figure 6 shows the velocity profiles at $x = 30$ mm for different SiC-MOSFETs operated with frequencies ranging from 25 kHz to 100 kHz. The peak velocity increased by increasing the repetitive pulse frequency regardless of the types of the SiC-MOSFETs. In addition, the position where the peak velocity was obtained was closer to the wall by increasing the repetitive pulse frequency. The velocity profiles showed a similar trend between the cases of MOSFET A and B. Clearly, the velocity profile obtained by MOSFET C indicated a larger peak velocity than those obtained by MOSFET A and B in all frequency cases.

Figure 6. Velocity profiles at $x = 30$ mm for different SiC-MOSFETs.
Figure 7a shows the time-averaged thrust generated by the DBD plasma actuator as a function of the repetitive pulse frequency for different SiC-MOSFETs when the voltage of the DC power supply was set to 1000 V. The generated thrust $T$ in the $x$-direction can be evaluated using the time-averaged velocity profile of the induced flow as follows [34]:

$$T = \rho \int u^2 dy,$$

where $\rho$ is the air density and $u$ is the $x$-component of the induced flow velocity. The thrust estimated by this simple method depends on the location of the velocity profile; however, this simple method provides a reasonable estimation of the thrust generated by the DBD plasma actuator [6]. The more sophisticated methods should be employed to calculate the thrust more precisely [35]. As reported in a previous study, the thrust increased almost linearly by increasing the repetitive pulses [15]. This result indicates that the thrust is proportional to the amount of generated charged particles. The thrust characteristics for the DC voltage of 1200 V are shown in Figure 7b. The larger thrust was produced by using 1200 V-DC voltage than that produced by using 1000 V-DC voltage owing to an increase in the total amount of the charged particles and an enhancement of the electric field for charged particle acceleration. We note that the thrust value for the DC voltage of 1200 V shows a similar result obtained in our previous work [15]. In addition, regardless of the repetitive pulse frequency and DC voltage, the thrust generated by the DBD plasma actuator with MOSFET C showed the largest value. Moreover, almost the same thrust values were obtained between the cases of MOSFET A and B. It should be noted that the thrust generated by MOSFET C became twice as that generated by MOSFET A and B, indicating that the characteristics of the SiC-MOSFET can significantly affect the performance of the DBD plasma actuators.

![Figure 7. Time-averaged thrust generated by DBD plasma actuator as a function of repetitive pulse frequency for different MOSFETs for DC voltages of (a) 1000 V and (b) 1200 V.](image)

Finally, we discuss the influence of the characteristics of the SiC-MOSFET on the thrust-to-power ratio. The thrust-to-power ratio is known as thrust effectiveness, which is employed to compare the performance of the DBD plasma actuator operated with different conditions [36]. Figure 8a denotes the thrust-to-power ratio as a function of the repetitive pulse frequency when the DC voltage is set to 1000 V. The power consumption was estimated by multiplying the pulse energy density and the repetitive pulse frequency, assuming that the power consumption is proportional to the repetitive pulse frequency [15]. The thrust-to-power ratio can be considered as the efficiency of DBD plasma actuators [12]. The highest efficiency was achieved by using MOSFET C in this study. The DBD plasma actuator with MOSFET A indicated slightly higher efficiency than that of the DBD plasma actuator with MOSFET B since MOSFET B requires more energy consumption while the thrust value was almost the same as the case of MOSFET A. The thrust-to-power ratio for the
case of MOSFET C decreased by increasing the repetitive pulse frequency. The generated thrust characteristics with MOSFET C showed a lower increase rate of thrust for higher repetitive pulse frequencies. Charged particles generated by a previous pulsed discharge could affect the thrust generation process in each pulsed discharge. An investigation of the thrust generation process for high repetitive pulse frequency cases in detail is needed to be carried out in future work. The thrust-to-power ratio for the case of the DC voltage of 1200 V is shown in Figure 8b. The basic trend of the efficiency coincides with the case of the DC voltage of 1000 V. However, the efficiency tends to become lower for the DC voltage of 1200 V compared to that for the DC voltage of 1000 V because the pulse energy is roughly proportional to the cube of the DC voltage while the thrust is proportional to the square of the DC voltage [37]. We demonstrated a significant difference in the induced flow field when SiC-MOSFETs, whose on-state resistance are different, were used. Similar flow fields were obtained in the case of MOSFET A and B, whose on-state resistance were similar to each other. The peak velocity increased from 1.8 m/s to 2.8 m/s, corresponding to the increasing ratio of 56% by changing the MOSFET A to MOSFET C when the DC voltage of 1200 V combined with 150 kHz pulses was applied. Consequently, the characteristics of the SiC-MOSFET (we mainly focused on on-state resistance) have an important role in the electrical and mechanical characteristics of DBD plasma actuators. In our experimental condition, in terms of thrust generation and efficiency, a SiC-MOSFET, whose on-state resistance is low, resulted in superior performance in the DBD plasma actuator.

![Figure 8](image_url)

**Figure 8.** Thrust-to-power ratio of the DBD plasma actuator as a function of repetitive pulse frequency for different SiC-MOSFETs for DC voltages of (a) 1000 V and (b) 1200 V.

### 4. Conclusions

In summary, we investigated the effect of SiC-MOSFET characteristics on the performance of the DBD plasma actuator driven by DC-biased repetitive pulses. Three types of SiC-MOSFETs, whose on-state resistance was different, were employed and inserted in a half-bridge circuit. Although the type of the SiC-MOSFET has a small impact on the fall time of the applied voltage, the rise time decreased by decreasing the on-state resistance. The applied voltage and discharge current waveforms generated by MOSFET C, whose on-state resistance was the lowest, showed a large difference compared to those generated by MOSFET A and B. The decrease in the rise time increased the pulse energy density. To characterize the mechanical performance, the flow field induced by the DBD plasma actuators was visualized by using PIV measurement. The result revealed that the DBD plasma actuator with MOSFET A and B failed to induce successive acceleration of the wall jet in our experimental condition. By contrast, the DBD plasma actuator with MOSFET C formed a successively accelerated wall jet, whose peak velocity was approximately 3 m/s when the repetitive pulse frequency and DC voltage were 150 kHz and 1200 V, respectively. These results suggest that the pulsed discharge process during the voltage-rising phase has an important role in the induction of the wall jet. The thrust generated by the DBD plasma actuators was roughly proportional to the repetitive pulse frequency. Notably,
the thrust in the case of MOSFET C indicated the twice value as the cases of MOSFET A and B, suggesting that the characteristics of the SiC-MOSFET can be significant to determine the performance of DBD plasma actuators. Moreover, in terms of the thrust-to-power ratio, the MOSFET C indicated the highest performance in our experimental condition. The lower on-state resistance results in shortening the rise time, enhancing the amount of the charged particle generation during the voltage rising phase.

To realize the practical applications of DBD plasma actuators, the development of a power supply, which is suitable for ionic wind generation, is an indispensable task. Further exploration of an optimal power supply for DBD plasma actuators based on the electrical and mechanical characteristics revealed by previous studies [2] will contribute to advances in the industrial applications of DBD plasma actuators.

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