

# Enhancement of Non-Equilibrium Atmospheric Pressure He Plasma Discharges by Using Silicon Diode for Alternating Current

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**Abstract.** In this paper, we report that enhanced He dielectric barrier discharges (DBDs) using simple and inexpensive device, such as Silicon Diode for Alternating Current (SIDAC) and high voltage transformer at commercial frequency. The SIDAC is designed for direct interface with the ac power line as fast switching and pulse devices. Here, discharge characteristics of He DBDs using SIDACs connected in series are studied experimentally. It can be obtained by using 15 series SIDACs that a rapid voltage change at the SIDAC breakover is  $dv/dt \sim 20$  kV/ $\mu$ sec and the pulsed DBD current with a duration of  $\sim 200$  nsec reaches  $\sim 1$  A, 100 times larger than that of the normal DBD without SIDACs. Emission intensity of He DBD is also increased strongly by series SIDACs to be  $\sim 100$  times larger compared without the SIDACs.

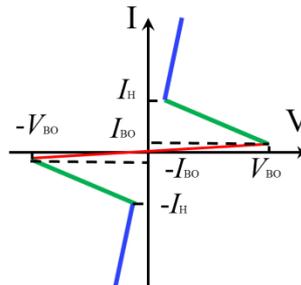
## 1. Introduction

The non-equilibrium atmospheric pressure plasma discharges (APPDs) have various merits that easy handling of non-equilibrium plasmas and chemical reactivity. These favorable characteristics enable us to apply those to biological application, thin film fabrications with plasma CVD, surface modifications of materials, light source and display. Therefore, the non-equilibrium APPDs are one of the most useful discharges in the industry. Dielectric barrier discharges (DBDs) are one of the typical non-equilibrium APPDs. In order to obtain stable and efficient DBD plasmas it is usually required to use high voltage and high frequency power sources and/or high voltage pulse sources with high repetition rate. When large volume DBD plasmas are necessary for environmental and engineering applications, generation of such plasmas also requires expensive and complicated power sources. In this paper, we have been studied the enhancement effects of atmospheric He DBD plasmas by using a Silicon Diode for Alternating Current (SIDAC) as a simple high voltage power source with rapid voltage change.



**Table 1.** Basic properties of the SIDAC (Model No. K1V38(W))

Breakover voltage [ $V_{BO}$ ]	360 ~ 400 V
Breakover current [ $I_{BO}$ ]	0.5 mA
Hold current [ $I_H$ ]	50 mA
OFF state voltage [ $V_{DRM}$ ]	270 V
OFF state current [ $I_{DRM}$ ]	10 $\mu$ A
Switching Resistance [ $R_S$ ]	0.1 k $\Omega$
Thermal Resistance	15 $^{\circ}$ C/W

**Figure 1.** V-I characteristic of SIDAC

## 2. Experimental setup

### 2.1. What is the SIDAC?

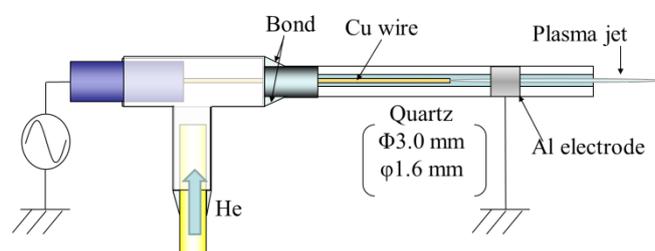
The SIDAC is designed for direct interface with the ac power line. The operation of the SIDAC is functionally similar to that of a spark gap. Figure 1 shows V-I characteristic of SIDAC. The SIDAC remains non-conducting until the applied voltage meets or exceeds its rated breakover voltage ( $V_{BO}$ ). Once entering this conductive state going through the negative dynamic resistance region, where conduction current is larger than the breakover current ( $I_{BO}$ ), the SIDAC continues to conduct, regardless of voltage, until the conduction current falls below its rated holding current ( $I_H$ ). At this point, the SIDAC returns to its initial nonconductive state to begin the cycle once again.

In general, the SIDAC is inexpensive and easy to use. In the present experiments, we used the SIDAC (Model No. K1V38(W)) made in Shindengen industry, which has the highest  $V_{BO}$ . Table 1 shows the basic properties of K1V38(W) used in the experiment. Although the  $V_{BO}$  is not enough high about 400 V for DBD plasmas, series connection of  $N$  SIDACs allows us to have much higher operation voltage given by  $V=N \times V_{BO}$ . For example, the switching voltage (effective breakover voltage) is increased to be 3,600 ~ 4,000 V with 10 series SIDACs.

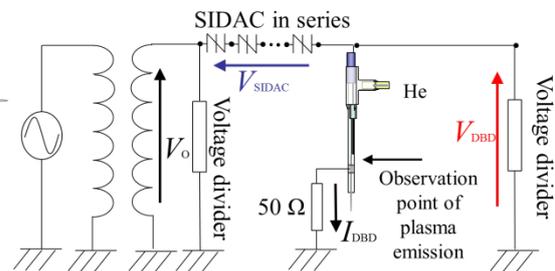
### 2.2. DBD plasma reactor and power source

Schematic view of DBD plasma reactor used in the experiment is shown in Figure 2. An inside electrode is copper wire and outside one is aluminium sheet, and a quartz tube with 3 mm outer diameter and 0.8 mm thickness is used as dielectric barrier between two electrodes. The length between two electrodes is 10 mm.

The electric circuit using SIDAC and high voltage transformer is shown in Figure 3, and the experimental condition is shown in Table 2. The secondary voltage of the high voltage transformer is kept at 12 kV<sub>PP</sub> at a frequency of 60 Hz. The SIDACs and DBD reactor are connected in series to apply SIDAC's high voltage switching to DBD. The number of the SIDACs in series is changed to be 4 patterns for 0, 5, 10 and 15. The SIDAC switching characteristic is checked using high voltage resistors and DBD plasmas as load. Rapid response of DBD plasmas at SIDAC switching phases are monitored electrically and optically. Time variation of emission intensity is observed by photo receiver (Model No. OE-200-UV, 190~1000 nm). The plasma emission is also measured by spectrometer and emission images are taken by digital camera.



**Figure 2.** Schematic view of DBD plasma reactor



**Figure 3.** Experimental circuit

**Table 2.** Experimental condition

Output voltage [ $V_o$ ]	12 kV <sub>pp</sub>
Frequency	60 Hz
Gas	He
Gas flow	4 slpm
No. series SIDACs	0, 5, 10, 15

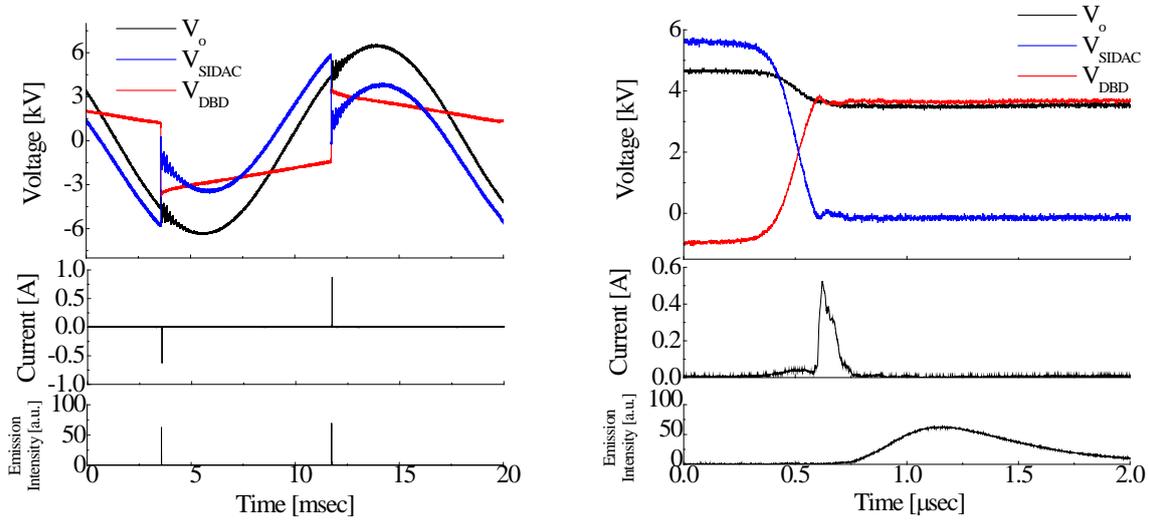
### 3. Experimental results

#### 3.1. Characteristic features of the DBD plasma

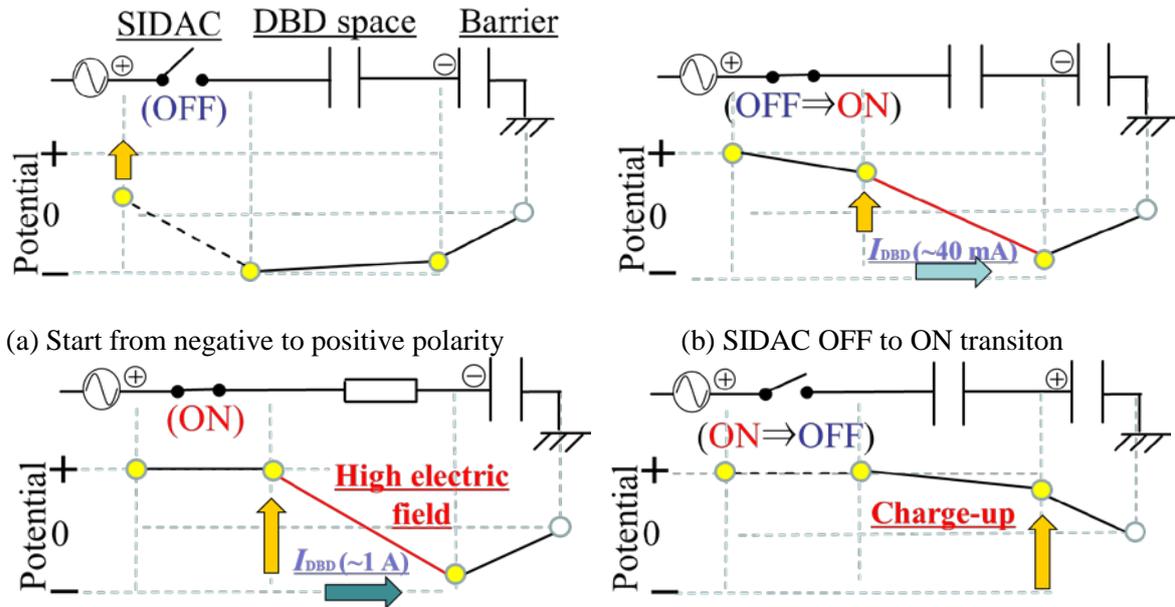
Figures 4(a) and (b) show waveforms of transform secondary voltage( $V_o$ ), SIDAC applied voltage( $V_{SIDAC}$ ) and DBD voltage( $V_{DBD}$ ), DBD current including the charging of DBD( $I_{DBD}$ ) and emission intensity from DBD when 15 SIDACs were used. When  $V_o$  meets or exceeds  $V_{BO}$ , SIDAC turns into the conductive ON state from OFF state quickly and a high voltage pulse is applied to the DBD plasma reactor simultaneously. Typical switching time of series SIDACs observed in the experiment is about 200 ns. The voltage rise rate of  $dV_{DBD}/dt \sim 20$  kV/ $\mu$ sec is obtained when 15 SIDACs are used. At the same time, small  $I_{DBD}$  of  $\sim 40$  mA can be seen firstly. After this small DBD event, second large DBD pulse of 0.5~1 A height and  $\sim 200$  ns width flows with a random delay time from the first DBD pulse. Corresponding to two DBD pulses visible light emission can be seen after  $\sim 20$   $\mu$ sec delay. DBD characteristics in positive and negative polarities are nearly same in the present configuration.

When DBD is used as a load of the SIDAC circuit connected in series, the electric circuit should be governed by two switching characteristics, one is SIDAC switching and the other is DBD itself. The switching characteristics and generation of DBD at the positive switching phase are schematically shown in Figure 5. Firstly as shown in Figure 5(a), after previous DBD in the negative polarity  $V_o \sim V_{SIDAC}$  goes up positively under the condition of  $V_{SIDAC} < N \times V_{BO}$ . In this phase, SIDAC is off state and no DBD current flows. The capacitor of dielectric barrier should be negatively charged and the circuit voltage from the transformer is dominantly applied to the SIDAC. When  $V_{SIDAC}$  exceeds  $N \times V_{BO}$  SIDAC turns to be on state simultaneously and the voltage applied to DBD electrodes increases quickly as shown in Figure 5(b) and (c). At this phase, first small current pulse with a peak of several tens mA are generated. Since the SIDAC used in the present experiments requires  $I_{DBD} > 50$  mA for the holding current to keep a continuous ON-state, SIDAC forces to turn off the DBD current if  $I_{DBD} < 50$  mA transiently. The peak current of the first DBD pulse might be determined by the transient voltage applied to DBD at the SIDAC switching phase. So far the reason why the second DBD pulses observed in the experiments have such high current peak of  $\sim 1$  A is not clear, but it is speculated that the first DBD current is dominated by both DBD start-up and SIDAC transient switching characteristics. Probably, applied high electric field to DBD space by high speed SIDAC's switching is caused second large DBD pulse. It may come from the triggering effect of the remaining first DBD plasmas. Voltage is applied to the DBD space when SIDACs turn ON state, the discharge current of the first pulse discharge is eliminated because it cannot maintain a stable on-state. In the above state of the second pulse, SIDACs are on state from the voltage measurement data. It is considered that

electron density associated with the discharge plasma by the first pulse attenuated as passage of time, but the second pulse discharge is formed stronger by small electronic discharges of first pulse. In the final stage shown in Figure 5(d), DBDs are terminated by charge-up effect of positively charged DBD barrier. Finally, the SIDACs return back to a non-conductive state and wait the following switching phase at the negative polarity.



(a) One cycle (b) Enlarged view at the SIDAC OFF/ON transition  
**Figure 4.** Waveforms of voltage, such as  $V_o$ ,  $V_{SIDAC}$  and  $V_{DBD}$ ,  $I_{DBD}$  and emission intensity when 15 SIDACs are used



(c) High current pulse appear by high electric field (d) DBD stop with decreasing potential difference by charge up

**Figure 5.** Relationship between SIDAC switching at the positive phase and DBD

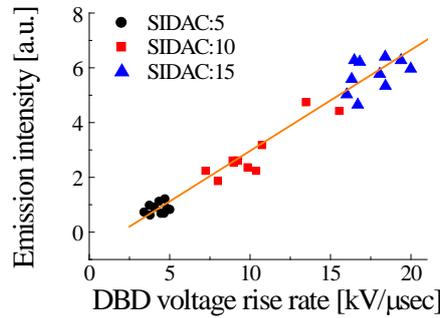


Figure 6. Relationship between emission intensity and  $dV_{DBD}/dt$

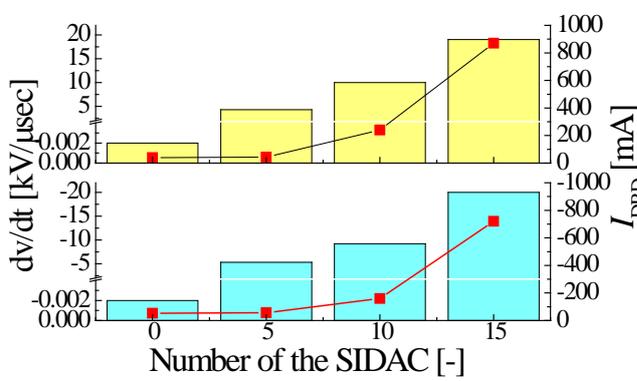


Figure 7. Relationship between  $dV_{DBD}/dt$ ,  $I_{DBD}$  and number of the SIDAC

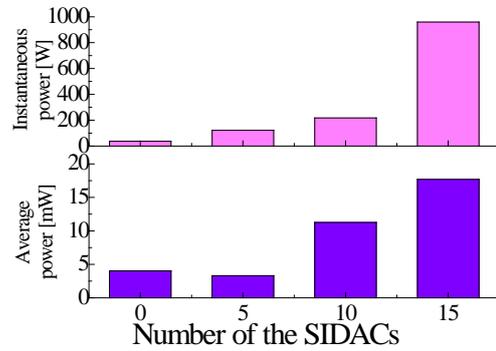


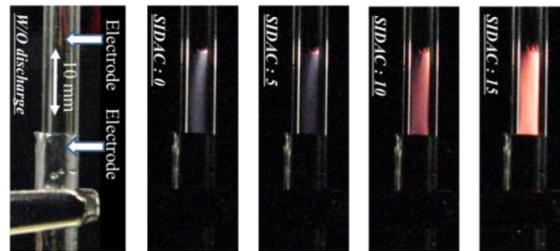
Figure 8. Instantaneous and average power against number of the SIDAC

Figure 6 shows relationship between the visible light emission intensity and  $dV_{DBD}/dt$  at the SIDAC OFF/ON switching in the positive polarity. The value of  $dV_{DBD}/dt$  increases with increasing the number of connected SIDACs in series, and the emission intensity also increases in proportion to  $dV_{DBD}/dt$ . Direct cause of this result is that discharge voltage which applied to DBD space is higher by large  $dV_{DBD}/dt$ . Figure 7 shows summary of the SIDACs characteristic by different polarity. It can be obtained by using 15 series SIDACs that a rapid voltage change at the SIDAC breakover is  $dV_{DBD}/dt \sim 20$  kV/ $\mu$ sec and the pulsed DBD current reaches  $\sim 1$  A, 50 times larger than that of the normal DBD without SIDACs. Figure 8 shows the instantaneous and average DBD power against number of SIDAC. Average power is also increased by series SIDACs to be  $\sim 5$  times larger compared without the SIDACs. The reasons why average power decrease in series 5 SIDACs are the timing of the DBD is defined by breakover voltage of the connecting SIDAC, and greatly reduced the number of discharge than without SIDAC.

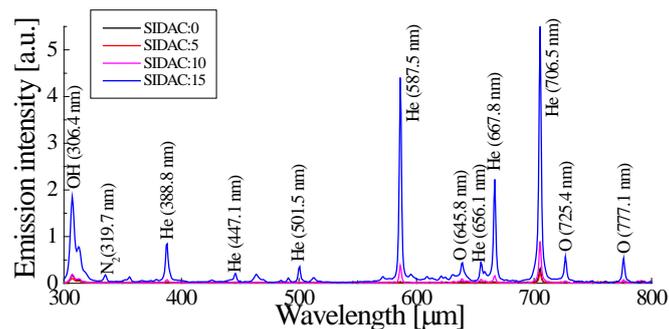
### 3.2. Spectroscopy of He plasmas

In this section, we show the result of He plasma emission spectroscopy. Pictures of He plasmas between two DBD electrodes are shown Figure 9. Shutter speed of CCD camera is set at 100 msec, so these pictures integrate the plasma emission for nearly 6 periodic cycles. The plasma emission doesn't show any drastic change at 5 SIDACs. However, when 10 or 15 SIDACs are connected in series, He plasma emission is increased strongly.

Spectroscopic results of He plasma emission are shown Figure 10. Shutter speed of CCD detector of a polychromator is set at 19 msec, and the number of averaging is 60 times. He(I) intensities of 558.5 nm and 667.8 nm show that increasing  $\sim 100$  times compared that without SIDACs. Plasma emission does not show any spectra of electrode material impurities. Therefore the enhancement of visible emission shown in Figure 9 is caused by the increase of the densities of DBD plasma density.



**Figure 9.** Pictures of He plasma emission by changing the number of connected SIDAC in series



**Figure 10.** He plasma emission spectrum between two electrode

#### 4. Summary

This paper has reported that enhancement effects of He APPDs by using Silicon Diode for Alternating Current (SIDAC) and high voltage transformer in series. Series connection of  $N$  SIDACs allows us to obtain high voltage pulse easily and simply, where the pulse operation voltage is given by  $V=N \times V_{BO}$ . For an example of the SIDAC application generation of DBD plasmas were tested and strong enhancement by SIDAC was observed. By using 15 series SIDACs a rapid voltage change of  $\sim 20$  kV/ $\mu$ sec at SIDAC breakover was obtained in the several kV range and the large pulsed DBD current with a peak of  $\sim 1$  A and a duration of  $\sim 200$  nsec was obtained. The emission intensity from He DBD plasmas has a linear relation with  $dV_{DBD}/dt$ . The increase of the emission intensity mainly comes from He(I) emission of 558.5 nm and 667.8 nm, which is  $\sim 100$  times larger compared without using the SIDACs. As the results, it can be concluded that a simple circuit configuration of SIDACs connected in series and high voltage transformer can be applied to generate efficient atmospheric DBD plasmas with high radical density.

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