REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
09-09-2017	Final Report	21-Apr-2016 - 20-Apr-2017

4. TITLE AND SUBTITLE

Final Report: Silicon Carbide Semiconductor Array for Enhanced Surface Dielectric Barrier Discharge Driven Flow Control

5a. CONTRACT NUMBER: W911NF-16-1-0266

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER: 611103

5d. PROJECT NUMBER:

5e. TASK NUMBER:

5f. WORK UNIT NUMBER:

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S): ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S): 68503-EG-RIP.3

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER
UU	UU	UU	UU		Richard Miles / 609-258-5131

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 11-Sep-2017

Agency Code:

Proposal Number: 68503EGRIP **Agreement Number: W911NF-16-1-0266**

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DUNS Number: 002484665 EIN: 210634501
Report Date: 20-Jul-2017 Date Received: 09-Sep-2017
Final Report for Period Beginning 21-Apr-2016 and Ending 20-Apr-2017
Title: Silicon Carbide Semiconductor Array for Enhanced Surface Dielectric Barrier Discharge Driven Flow Control
Begin Performance Period: 21-Apr-2016 **End Performance Period:** 20-Apr-2017
Report Term: 0-Other

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 1

Major Goals: he DURIP equipment is associated with a separately funded ARO research effort on new nanosecond pulse driven surface plasma devices for enhanced control authority in high speed air, and on the use of these surface mounted plasma devices for the suppression of dynamic stall on helicopter blades. The goal is to establish a new capability that provides robust helicopter blade control over a wide range of frequencies with systems that are low weight and flush mounted, so very little flow perturbation occurs when they are not in operation. The DURIP equipment funds are supporting the fabrication of a new semiconducting surface that is intended to provide a significant increase in dielectric barrier discharge driven momentum transfer to the air passing over the helicopter blade.

Accomplishments: A new configuration of multi-diode asymmetric surface was designed and fabricated using high-current SiC diodes. The design was accomplished together with specialists from United Silicon Carbide, Inc. Thin (0.150 mm) metal strips are embedded in a dielectric matrix and connected together with SiC diodes that are sealed into the dielectric material. Individual 1 cm square panels each with 30 Schottky diodes embedded across the 1 cm width. The new SiC array was delivered and initial tests indicate that the diodes are operating as expected, with some further shielding work underway to suppress parasitic discharges around the periphery on the diode panel.

Training Opportunities: Nothing to Report

Results Dissemination: Andrey Starikovskiy, Richard B. Miles
Dielectric Barrier Discharge Control and Thrust Enhancement by Diode Surface (AIAA 2017-4159) 48th AIAA Plasmadynamics and Lasers Conference, 2017, 10.2514/6.2017-4159

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

Silicon Carbide Semiconductor Array for Enhanced Surface Dielectric Barrier Discharge Driven Flow Control

Defense University Research Instrumentation Program (DURIP)
W911NF-16-1-0266
(Award Period: April 21, 2016 – April 20, 2017)
Final Report

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UNITED STATES

Objective

The requested equipment will enable us to explore the possibility of increasing the surface jet velocity by using a dielectric material with fast acting silicon carbide semiconductors embedded into it. This configuration is expected to overcome the problem of reverse breakdown, enabling short high voltage pulses to couple much more effectively to air. If successful this will produce a high-speed jet in the boundary layer near the surface, possibly ten times higher than AC driven conventional dielectric barrier devices and at repetition rates of more than 100 kHz. Very little energy is required due to the high efficiency coupling of the high voltage pulses to non-thermal modes of excitation.

Approach

Funds were requested for developing a new semiconducting substrate for fast acting control of flows over airfoils to prevent dynamic stall and provide improved lift. The key element of the structure is a miniature high-frequency, high-voltage blocking Schottky diode. United Silicon Carbide, Inc offers the xR series of high-performance SiC Schottky diodes. With zero reverse recovery charge and 175°C maximum junction temperature, USCI's diodes are ideally suited for high- frequency and high-efficiency power systems with minimum cooling requirements. Typical direct voltage for the entire structure based on these diodes could be as low as $U_R = 30\times1.25V = 37.5$ V/cm. Peak direct current is adjusted to ~50 A. Breakdown voltage reaches $U_B = 30\times650V = 19500$ V/cm. The equipment proposed allows a significant improvement in ionic wind generation by surface dielectric barrier discharges due to high efficiency in backward breakdown suppression and possibilities for high-frequency operations.

Relevance to Army

High speed helicopters must accommodate significant changes in the rotor lift performance as a function of rotor angle. The advancing blade can achieve transonic conditions while the retreating blade experiences relatively low speed. The high Mach number of the advancing blade requires an angle of attack below 5 degrees for maximum lift, whereas the retreating blade requires high an angle of attack in excess of 10 degrees. Under high speed and high load conditions, stall occurs during the retreating cycle and destabilizes the aircraft. Thus operation requires that the angle of attack of the blades be changed during the cycle and optimized with flight speed. The focus of this research is to develop a new type of plasma actuators which can be used to optimize high speed flight performance, particularly focusing on suppressing the dynamic stall by retreating blade separation control.

Accomplishments for Reporting Period

- New configuration of multi-diode asymmetric surface was developed using high-current SiC diodes. Thin (0.150 mm) metal strips are embedded in a dielectric matrix and connected together with SiC diodes that are sealed into the dielectric material (Figure 8). The number of the diodes has been reduced to 30 across a 1 cm square tile, corresponding to a 0.33 mm cycle spacing.

Collaborations and Technology Transfer

Multi-diode asymmetric surface development is made in close collaboration with United Silicon Carbide, Inc. USCi is responsible for customized SiC Schottky diodes fabrication and micro-assembly.

Resulting Journal Publications during Reporting Period

1. Andrey Starikovskiy, Richard B. Miles
   Dielectric Barrier Discharge Control and Thrust Enhancement by Diode Surface (AIAA 2017-4159) 48th AIAA Plasmadynamics and Lasers Conference, 2017, 10.2514/6.2017-4159

Graduate Students Involved During Reporting Period

- Kristofer Meehan (grad student)

Awards, Honors and Appointments

- None

Design of New Silicon Carbide Semiconductor Array

In previous work we undertook a design project to develop a new semiconducting substrate. That concept is shown in Figure 1. With DARPA funding, we worked with United Silicon Carbide, Inc. to design a preliminary device with Schottky barrier diodes inlaid into the surface as shown in Figure 2. Between each diode pair there was an exposed slat of metal to allow the surface charge to enter the diode chain. Diodes were spaced at 18 micron intervals and 5 mm tiles were fabricated and assembled into 3 by 13 arrays. A picture of this device is shown in Figure 3.

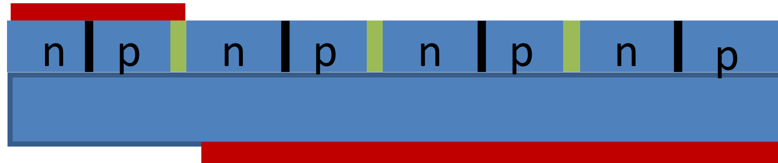

Figure 1. Semiconducting dielectric concept for suppression of backward breakdown.

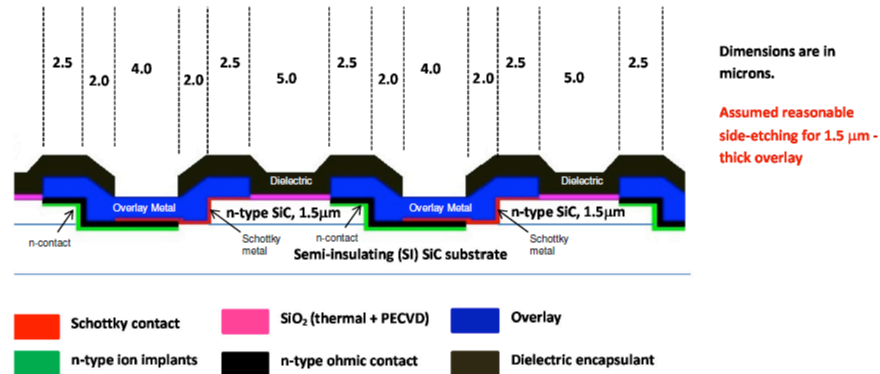

Figure 2. Preliminary design and suggested fabrication procedure by United SiC, Inc. for semiconducting dielectric material concept for suppression of backward breakdown.

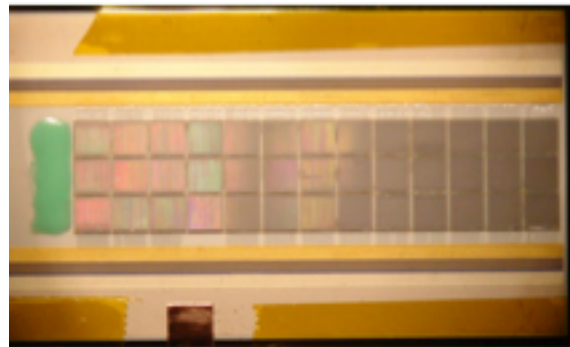

Figure 3. Tiled SiC array fabricated by United Silicon Carbide.

Silicon carbide semiconducting material is chosen for this application since it can withstand high voltages without breakdown, switches in nanoseconds and is exceptionally strong. It can be applied in small strips so it can be configured for various internal and external flow geometries. The junctions are formed on a low conductivity SiC substrate with an n doped epitaxial layer. The layer is etched and doped by ion implantation to provide sequential transverse pn junctions.

This device was a preliminary attempt to achieve the required suppression of backward breakdown, however tests indicated that it was not achieving that goal except at very low pressure. Subsequent examination established several critical problems:

1) The edges of the 5 mm tiles were trimmed, and therefore did not sustain the performance of the diode, allowing a short circuit along each edge.
2) The small separation between the tile blocks created a channel for the discharge, especially at pressures approaching ½ atm and higher, preventing the charge transfer to the tile surfaces.
3) The tiles were connected with thin gold wires, which were easily broken and tended to attract attract the discharge at higher pressures.
4) The "switch on" voltage for forward diode conduction was approximately 500 volts, too high to suppress the reverse breakdown in the already ionized air over the diodes.

We have developed a major redesign that is configured to avoid these pitfalls. In this revised case, thin (0.150 mm) metal strips are embedded in a dielectric matrix and connected together with SiC diodes that are sealed into the dielectric material (Figure 4). The number of the diodes has been reduced to 30 across a 1 cm square tile, corresponding to a 0.33 mm cycle spacing.

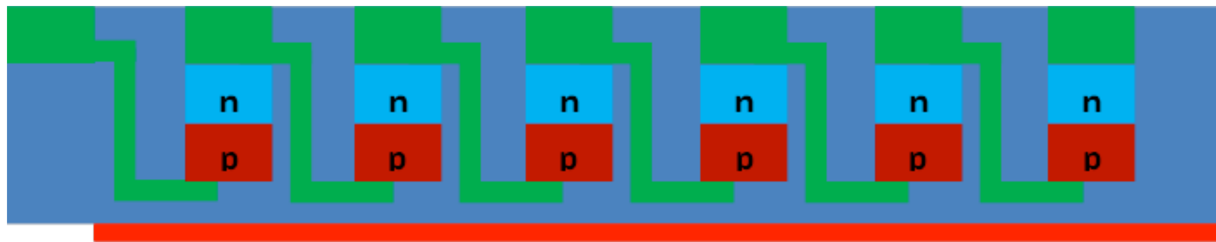

Figure 4. New semiconducting dielectric concept for suppression of backward breakdown. Green, red – metal layers; Blue – dielectric material; np – 1A, 650V blocking SiC Schottky diodes.

The surface demonstrated in Figure 4 has a selective conductivity. The negative polarity pulse will generate the surface dielectric barrier discharge above the surface from left to right, while the backward breakdown is suppressed because of high reverse conductivity of the structure. The key element of the structure is a miniature high-frequency, high-voltage blocking Schottky diode. United Silicon Carbide, Inc offers the xR series of high-performance SiC Schottky diodes. With zero reverse recovery charge and 175°C maximum junction temperature, USCI's diodes are ideally suited for high- frequency and high-efficiency power systems with minimum cooling requirements. These diodes feature:

- Positive temperature coefficient for safe operation and ease of paralleling
- 175°C maximum operating junction temperature
- Extremely fast switching not dependent on temperature
- Essentially no reverse or forward recovery
- Maximum DC forward current: 1 A
- DC blocking voltage: 650 V
- Forward voltage: 1.25 V

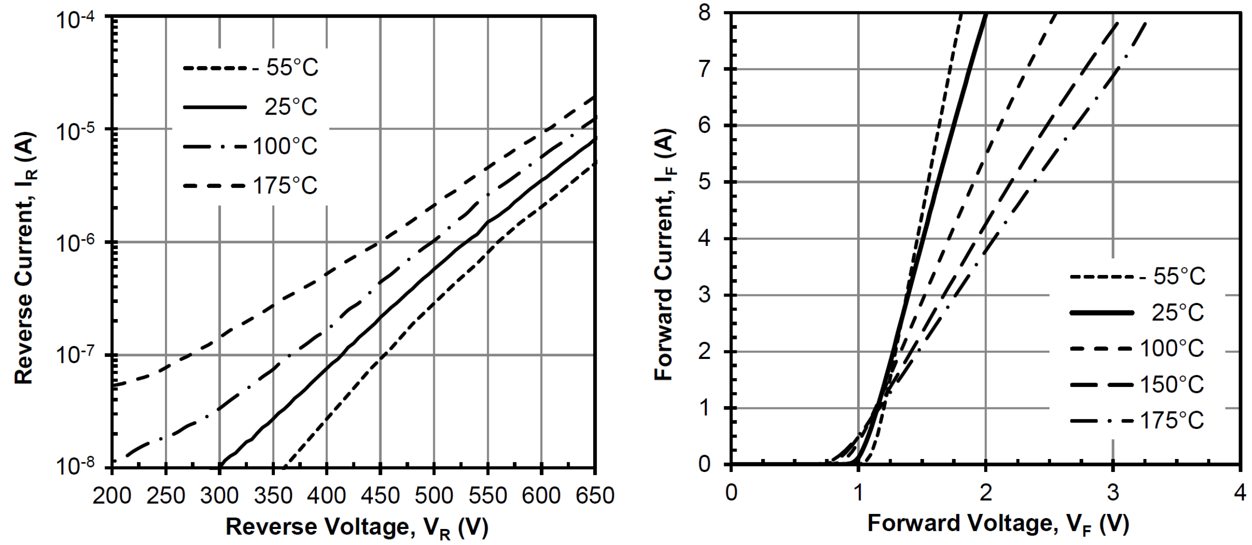

Figure 5. Typical performance of blocking SiC Schottky diodes. A) Reverse characteristics; B) Forward characteristics.

Figure 5 summarizes the performance of the SiC diodes. Typical direct voltage for the entire structure based on these diodes could be as low as U_R = 30×1.25V = 37.5 V/cm. Peak direct current is adjusted to ~50 A. Breakdown voltage reaches U_B = 30×650V = 19500 V/cm.

The proposed design allows solving all major problems of the previous version. Specifically, there are no edges and gaps between separate blocks; no exposed connecting wires; much lower direct voltage. Breakdown voltage is limited by ~20 kV, which allows using a wide range of experimental conditions. Very high operational temperature of the diodes (up to 175C) allows high-frequency operations.

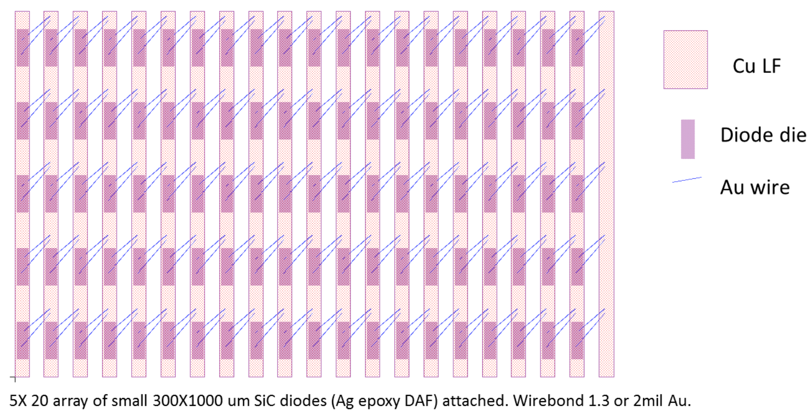

Figure 6. QFN diode array – assembling design by United SiC, Inc. for semiconducting dielectric material concept for suppression of backward breakdown.

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Figures 6, 7 demonstrate the assembling design for a QFN diode array. The actual design is shown in figure 8.

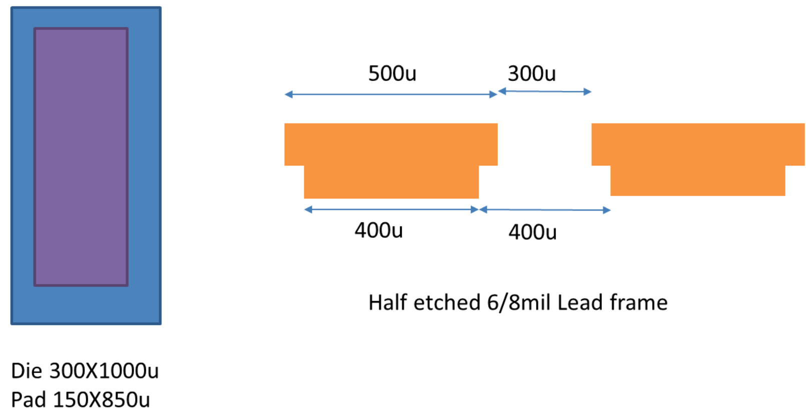

Figure 7. Die size and lead frame details.

QFN diode array manufacturing and assembling

The first step of QFN packages assembling was a custom SiC diodes fabrication. Device yields were excellent, ~99% on three of four wafers. Wafer #1 has somewhat reduced yield, ~92%, possibly related to the intrinsic wafer defects. Low forward voltage drop, $V_f \sim 1.4$ V, has been demonstrated at rated forward current $I_f = 1$A per diode. Low reverse leakage currents, Ir < 50 nA, have been demonstrated at rated blocking voltage $V_r = 650$ V.

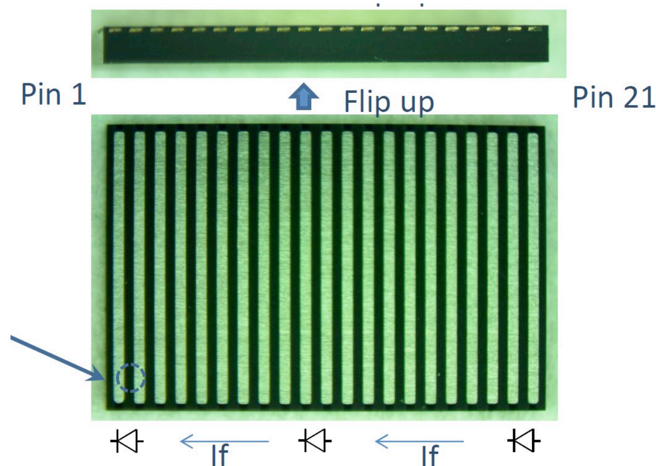

Figure 8. Photo of actual design of the QFN package.

Figure 8 demonstrates the design of the diode surface. Conductive stripes are connected to each other by SiC diodes. The distance between conductive strips is about 0.4 mm. These gaps are filled by plasma during the high-voltage pulse. Above the conductive surfaces the electric field is much weaker than in the gaps, but because of small strips size the plasma zones overlap each other at some distance above the surface.

Figure 9,a demonstrates typical blocking characteristics between adjacent pins of the package. It is clear that the interelectrode voltage could be as high as 800 V at rather low reverse current (less than 1 μA). Thus, the mean electric field in the gap could reach E = 800/0.04 = 20 kV/cm. This electrical field is below the breakdown threshold. It means the discharge will

propagate by streamer mechanism at atmospheric pressure conditions. At low pressure conditions (100-400 Torr) one could expect a homogeneous breakdown development.

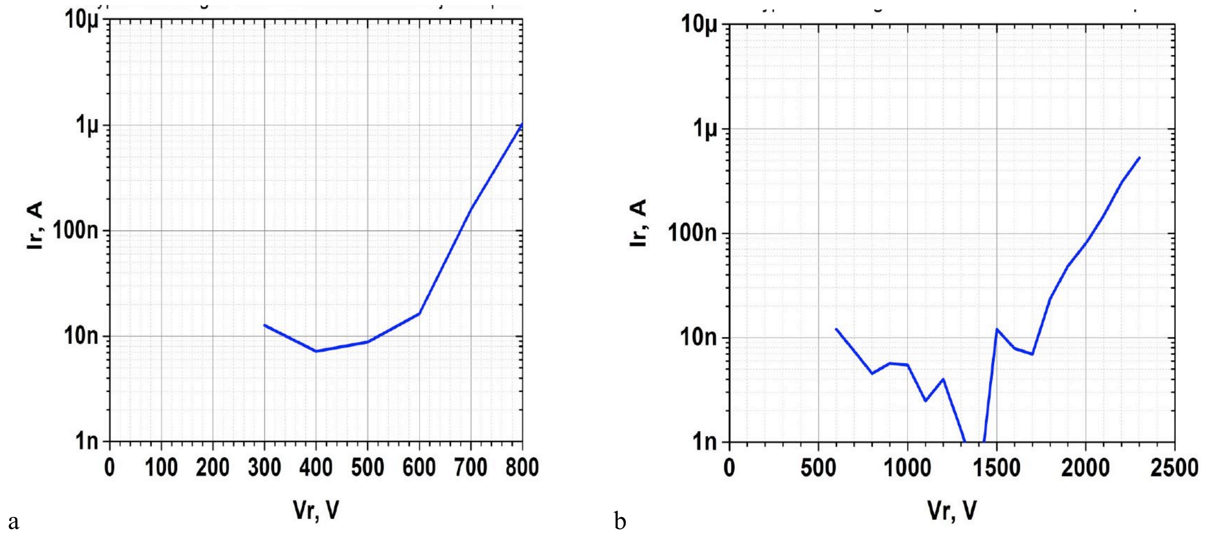

Figure 9. QFN package typical blocking IV characteristics
a) between adjacent pins; b) across 4 pins

Figure 9,b demonstrates the scalability of the current-voltage characteristics across several pins. It is clear that the voltage increases in proportion to the number of diodes and remains the same for each individual gap for specified reverse current. Forward IV characteristics demonstrate the ability of the surface to suppress the reverse discharge in plasma layer. Figure 10,a shows the ability of the surface to conduct the current about 5-6 A/cm at typical electric field E ~ 45 V/cm. This electrical field is very small to maintain the current through the plasma layer.

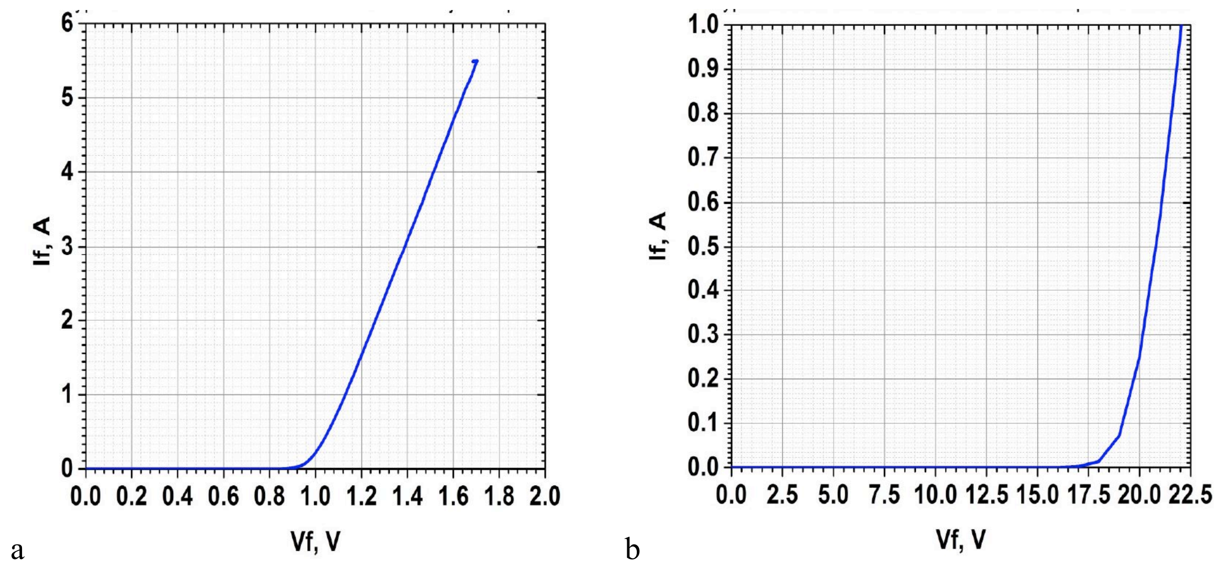

Figure 10. QFN package typical forward IV characteristics
a) between adjacent pins; b) across 4 pins.

Figure 10,b demonstrates the scalability of the forward IV characteristics for the package across 4 pins. The direct proportionality of the effective resistivity with the number of pins is shown. All usable QFN packages were verified to conduct forward current between pins 1 and 21. $V_f = 22V$ at $I_f = 1A$ ($R_{on} \sim 2.2$ Ohm).

The proposed design allows solving all major problems of the previous version. Specifically, there are no edges and gaps between separate blocks; no exposed connecting wires; much lower direct voltage. Breakdown voltage is limited by ~20 kV, which allows using a wide range of experimental conditions. Very high operational temperature of the diodes (up to 175C) allows high-frequency operations.

Preliminary test results

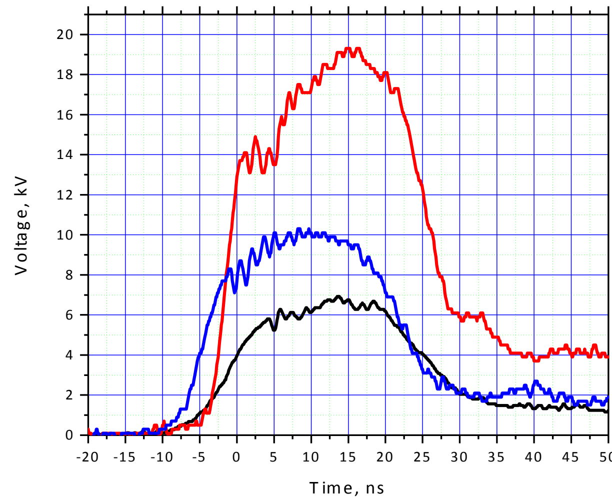

Figure 11. NS high-voltage pulses used in experiments.

Figure 11 shows the oscillograms of high-voltage pulses used for plasma formation experiments. Three voltages were used: 20 kV, 10 kV and 7 kV. The pulses have a typical rise time ~3 ns, and a total pulse duration ~25 ns. Figure 12 demonstrates dynamics of the emission of second positive system of nitrogen ($N_2(C^3)\rightarrow N_2(B^3)$ transition) in air. Fast quenching of the upper state by molecular oxygen allows to trace the dynamic of the state excitation by electron impact. The time step between frames is 1 ns, and the ICCD camera gate is also 1 ns. It is clear that the SiC diode surface for the pulse polarity chosen acts almost as a conductive cupper strips and suppresses the plasma formation over the surface. It means that the conductivity of SiC surface is high enough to redistribute the electric potential and reduce the electric fields. The discharge propagates only above the dielectric surface around the metal strips and the diode surface (Figure 12). After t=25ns above the dielectric surface the reverse breakdown formation is observed. The SiC surface shows no reverse discharge in these conditions. This demonstration indicates the possibility to control the reverse breakdown even at high pressure conditions using diode surfaces.

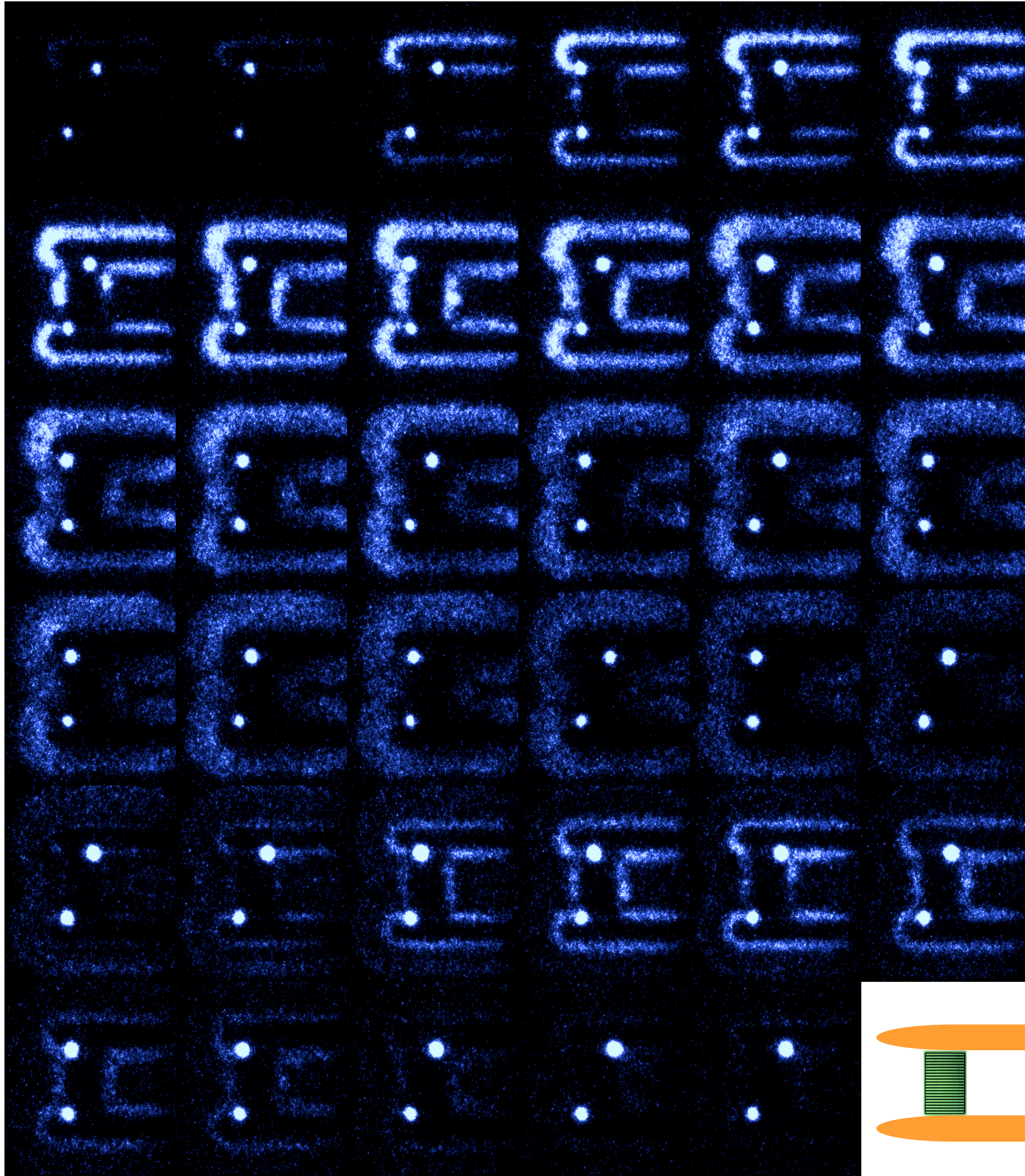

Figure 12. NS SDBD discharge development and plasma generation over the SiC diode surface. U = 20 kV, P = 1 atm, air. Camera gate t = 1 ns, step between frames dτ = 1 ns.

Summary

New configuration of multi-diode asymmetric surface was developed using high-current SiC diodes. The new equipment allows a significant improvement in ionic wind generation by surface dielectric barrier discharges due to high efficiency in backward breakdown suppression and possibilities for high-frequency operations. New SiC diodes-based design is proposed to increase the induced jet velocity. The design demonstrates much better performance than an old version of SiC-based diode surface.