Paper

Early Stage of Pulsed High Current Discharge with Copper Powder

Takuma Yokoyama* Student Member
Takuya Kuraoka* Member
Kazuya Takano* Student Member
Shinji Ibuka* Member
Koichi Yasuoka* Member
Shozo Ishii* Member

Early phase of powder plasmas powered by a pulsed high current discharge was examined by use of high-speed cameras and a laser shadowgraph and schlieren techniques. Initial electrons created by a pre-ionization discharge collide with both an anode and powder particles, of which surfaces evaporate after then. Evaporation of the particle by electron collision initially occured in the hemisphere surface which is close to cathode side. Since vaporization of the anode far exceeds that of the particles, discharge characteristics is almost similar to that of vacuum sparks in which expanding anode plasmas are observed. In order to suppress the developpment of the anode plasma, reduction of the effective anode area by varying the anode shape was examined.

Keywords : powder, dense plasma, pulsed discharge, vacuum discharge, vaporization

1. Introduction

We proposed to create a plasma using metallic powder injected between electrodes by a pulsed discharge in vacuum(1). The powder injection was controlled by electrostatic forces, which worked successfully to manipulate tiny particles in vacuum. The production of plasma from powder has various advantages in comparison with that using gases, which are widely applied in plasma sources. When gases are replaced with the powder in gas-puff z-pinches, control of the spatial distribution of transiently injected powder is easier because of its larger mass, which makes a diffusion velocity slower than that of gases. To the author's knowledge, only one paper was published reporting that dense plasmas were produced using powder(2).

There, of course, are plasmas created from the solid materials, such as fiber pinches, laser ablation plasmas, and wire array z-pinches. Although they can produce the dense plasmas, they have a drawback of the low repetition rate of operation. On the other hand, the powder has fluidity like gases that makes the high repetition rate operation possible.

There are variety of applications of the powder plasma such as intense soft x-ray sources, formation of fine particles, and thin-film deposition in material science. Since the powder is solid, there are more kinds of material to become plasmas in comparison with gases. Consequently, peculiar fine particles and thin-films are accomplished that cannot be obtained with the gaseous plasmas. When the electrical energy is discharged into a single particle of the powder, a microplasma that is recently attracting the attention of researchers in the field of plasma applications can be created. The powder discharge is a candidate of the new method to create microplasmas.

In this paper, the early stage of the powder discharge was examined with optical measurements. Initial electrons created by a preionization discharge collide with both an anode and powder particles, of which surfaces evaporate after then. However, the evaporation of the anode surface was remarkable in a plate-plate electrode system, that was the dominant phenomenon in vacuum sparks. In order to suppress the developpment of the anode plasma, reduction of the evaporating anode area by varying the anode shape was examined.

2. Experimental Setup

We employed spherical copper powder with the diameter of about 100 μm, of which shape observed by a micrograph is shown in Fig. 1. Since copper has been often used in the experiments such as exploding wires(3)(4) and fiber pinches, it is easy to discuss the discharge characteristics of copper. The particles are spherical and their diameters are almost the same. The powder has to be precisely manipulated spatially and temporally between the discharge electrodes in order to produce the powder plasma with good reproducibility. The powder injection has to be accomplished with the fixed spatial distribution and to be synchronized with the discharge. We have tried various

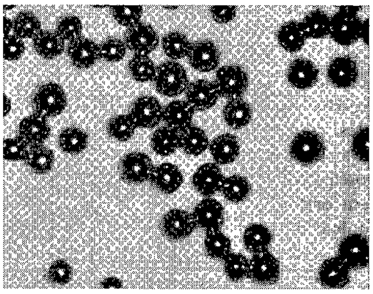


Fig. 1. Micrograph of the spherical copper powder particles with a diameter of 100μm

---

* Department of Electrical and Electronic Engineering,
Tokyo Institute of Technology
2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552

methods to inject the powder between the discharge electrodes. An electrostatic method has been adopted because it makes the handling of powder in vacuum easy and establishes the good controllability.

A schematic of the experimental setup is shown in Fig. 2. A powder injection system is placed under the main discharge electrodes. Two circular plate electrodes are separated by an acrylic insulating spacer with the thickness of 10 mm and the inner diameter of 16 mm. The upper electrode is used as the cathode of main discharges and has a hole of 2 mm in diameter at the center for the powder injection. The surface of the lower electrode is shallowly cut conically so that the powder particles can always roll back to the central region of the electrode after each shot. A rectangular pulsed voltage with a voltage of 10 kV and a pulse width of 100 ms was applied for the particles to be accelerated between the electrodes. When the voltage is applied, the particles are charged to Q written as⁽⁵⁾

$$Q = \frac{2}{3}\pi^3 \varepsilon_0 r^2 E_0$$

where r is the particle radius, E_0 is the electric field, and ε_0 is the dielectric constant in vacuum. When the electrostatic force working on the particle with the charge of Q is greater than the gravitational force, the particle is lifted up and is accelerated toward the opposite electrode. Afterwards, the particle is ejected through the hole of the upper electrode to the discharge region.

The powder discharges were powered by a capacitor of 0.5 μF charged to 20 kV. Since we focused to study on the early stage of the powder discharges, the capacitor energy was kept as low as possible to avoid the unnecessary electrode erosion by high-current discharges. The electrode separation was 10mm for the main discharge. The discharge electrodes and the powder injection system were placed in a stainless vacuum chamber evacuated at a pressure of 10^{-5} Torr (10^{-3} Pa). The tungsten, which has a high boiling point (3680K), was used as the electrode material to reduce the electrode erosion. The circular plate cathode was grounded. The powder was injected before 100 ms prior to the main discharge.

Since the injected particle distribution was spatially sparse, it appeared to be difficult for the powder itself to initiate the discharge in vacuum. To create a powder discharge with good reproducibility, a preionization system was required to supply a sufficient amount of initial electrons. We placed a tungsten wire electrode in the cathode as shown in Fig.2 for the preionization discharge that was powered by a capacitor of 5400pF.

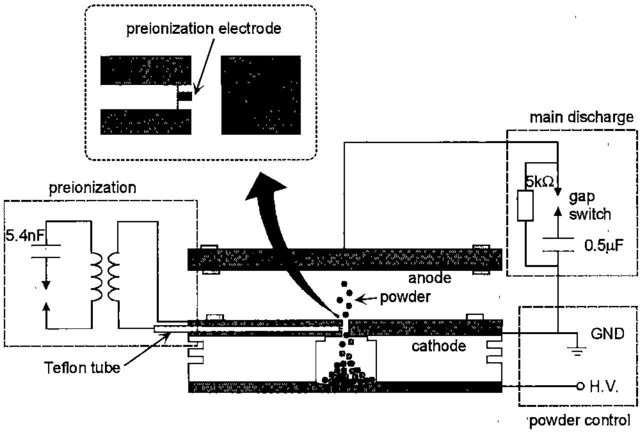


Fig. 2. Experimental setup of the powder discharge

At the beginning of the experiments of which results are described in Chapter 3, the electrode configuration was different from that shown in Fig.2. The upper electrode was a cathode with the preionization electrode. The lower electrode was an anode with the hole. Since anode plasmas hampered plasma development, the electrode configuration was changed to the present one in such a way that various anode shapes were able to be examined as mentioned in Chapter 4.

3. Development Process of the Powder Discharge

The development of the discharges with and without powder in the plate-plate electrode system was examined using optical measurements, namely, a high-speed camera, laser-shadowgraphy, and schlieren method. The early stage of the discharges was observed with framing pictures taken by the Imacon 468 (Hadland Photonics). Discharge currents were measured using a Rogowskii coil. The temporal change of the total visible light emitted from the discharges was measured by a photo-multiplier guided by an optical fiber. In this experiment, the electrode configuration is different from that shown in Fig.2. The polarity of the main electrode was reversed with that shown in Fig. 2. The upper electrode was cathode in which the tungsten wire electrode for the pre-ionization discharge was placed. The powder was injected through the hole of the grounded anode.

The sequential pictures of the discharge without powder are shown in Fig. 3. Although these pictures were not taken in a same discharge, they were selected from those in different discharges as showing the typical profile at each time. When the capacitor was fired, the electrons generated by the preionization discharge were accelerated to the anode. Since there exists no powder between the electrodes, electrons collided directly with the anode, of which surface was heated and evaporated. The evaporated anode material formed the anode plasma that expanded toward the cathode as shown in the timing of ② and ③. The peak of the light intensity signal was due to the formation of anode plasma. These discharge characteristics are similar to those of vacuum discharges. In the framing pictures, the intense light emission from the anode plasma was observed above the anode until 0.5 μs. In the timing of ④, a dark region is observed near the cathode, that is supposed to the formation of sheath.

The discharge development with powder is shown in Fig. 4. The powder plays a role to change the discharge development. In the timing of ①, the light emission from the powder particles is observed and has the first peak in the total light signal. Since the surface of the particles was vaporized by the electron bombardment, the excited and ionized copper atoms emitted the light. The light intensity near the anode is stronger than that near the cathode. The light emission from the powder changes from being circular to being diffusive as shown in the timing of ②. In the timing of ③ and ④, the anode plasma expanded toward the cathode as was seen in the discharge without powder. A pinched plasma channel was formed in the region between the cathode and the anode plasma, of which separation was almost constant during the discharge as seen in the picture of ④ and ⑤. Since the plasma channel was supported by the voltage-drop across the sheath, the top surface acted as a virtual anode. The temporal change of the total light intensity has two peaks, which correspond

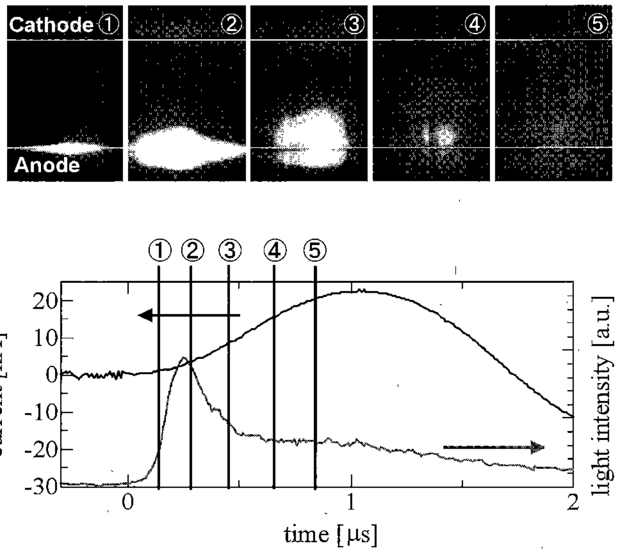


Fig. 3. Framing photographs of the vacuum spark

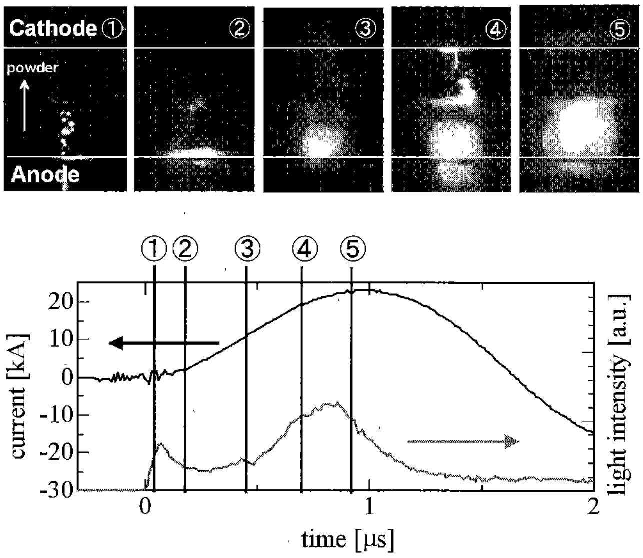
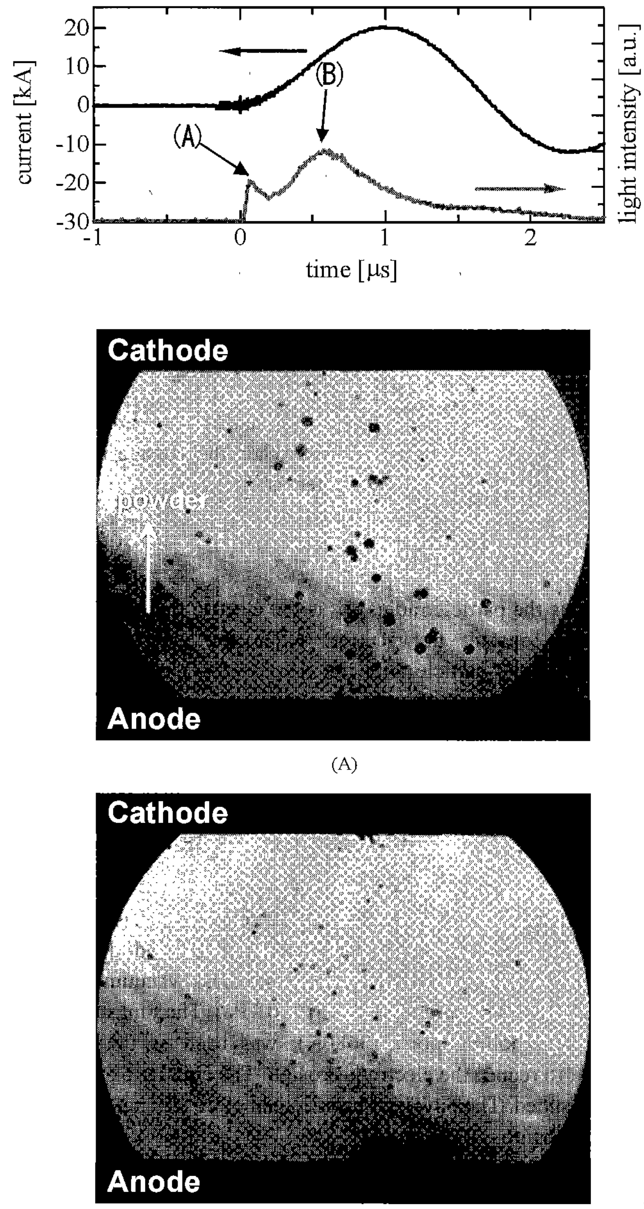


Fig. 4. Framing photographs of the powder discharge



(A)

(B)

Fig. 5. Shadowgraphs of the early stage of the powder discharge

to the light emission from the pinch plasma for the second.

We have to recognize whether the particles are vaporized completely or partly. However, framing pictures could not record the exact shape of the particles, which was screened by surrounding visible light. We employed the laser shadowgraph technique to observe the outer shape of the particles that was recognized as shadow of laser light prevented by them. The second harmonic wavelength of 532nm of a pulsed Nd:YAG laser with a pulse-width of 8 ns pulse was used. The shadowgraph was recorded on a Polaroid film.

Two representative shadowgraphs are shown in Fig. 5. At the beginning of the discharge, larger diameter shadows of the particle were found at the central part of the picture in Fig. 5(A). Since the high-density vapor of copper screens the laser light, shadow of the particles becomes larger when the evaporation from the surface are noticeable. The detailed structure of the shadow is realized by enlarging the shadowgraph of one particle as shown in Fig. 6. The evaporation by electron collision occurs only in the hemisphere surface which is close to cathode.

The dark region at the anode surface in Fig. 5(B) shows the vaporization of the anode material heated by electron bombardment. Here, the plasma column bridged between the cathode and the anode plasma as shown in Fig.4. Surprisingly, vaporization of the particle surface seemed to be suppressed, because the diameter of particle's shadow is not so large as in Fig. 5(A). There are two possible reasons for that the vaporization of the particles is not pronounced. The surface of the particle is not heated in the anode plasma to the boiling point. Since the electric field in the plasma is not remarkable, electrons cannot obtain enough energy to vaporize the surface.

The vaporization has to occur to the extent for the powder to establish the powder plasma. However, the evaporation of the anode surface was so remarkable, that the anode plasma dominated over the discharge development.

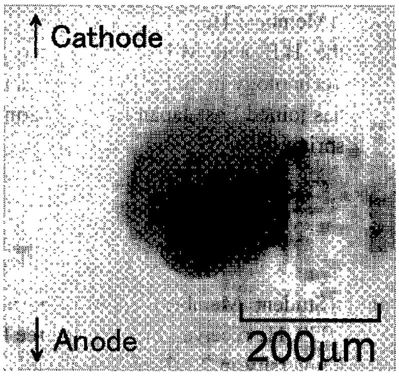


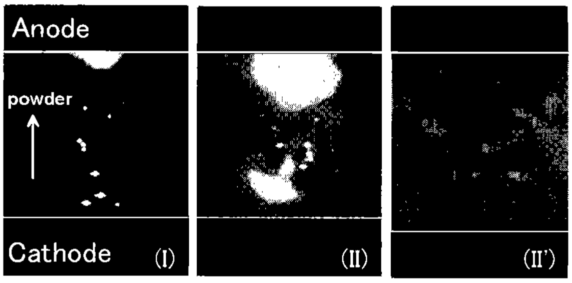
Fig. 6. Enlarged shadowgraphs of the particle taken at the timing (A)

4. Control of the Powder Discharge by Variation of the Anode Shape

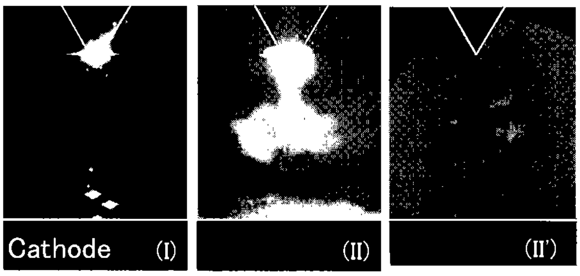
The anode-plasma developed with the large volume in the plate-plate electrode system as mentioned before. In order to suppress the growth of the anode plasma and to enhance the vaporization of powder, we tried to reduce the effective anode area with which electrons collided after being accelerated from the cathode. The anode shape was varied in two ways to reduce the volume of the anode plasma, namely, a conical tip or a truncated cone tip with a 2 mm diameter hole. The latter electrode tip was sharply edged.

The observation was carried out using the high-speed camera and laser schlieren method. The schlieren method resembles the shadowgraphy. Since it gives the information on the density gradient, one can obtain spatial profiles of the vapor and the powder more in detail. In Fig. 7 are summarized the results with the three types of the anodes, that included high-speed photographs and schlieren patterns. Framing pictures are taken at the time that is marked in the waveforms of the current and the total light intensity. At the time of (I) when the discharge is initiated, the diameter of the evaporated area was about 1 cm for the plate anode case, however, that decreased to about 0.6 cm for the discharges with the conical tip and the truncated cone tip with hole. The bright particle-images exist in wider region between the plate-plate electrodes. Since the electric field concentrates near the sharp tip, the electrons accelerated from the cathode tend to converge on the axis for the non-plate electrode cases.

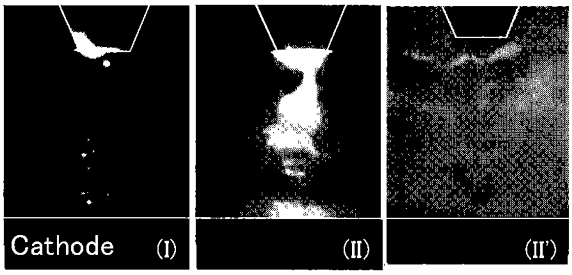
The anode plasma stayed locally near the tip of the non-plate anode during the discharge without powder as shown in Fig. 8. The non-plate anodes are effective for suppressing the growth of the anode plasma as shown in Fig. 7 (II). Since the powder was injected from the cathode as shown in Fig. 2, the discharge developments were slightly different from those shown in Fig. 4. In the timing of (II), the plasmas originated from the powder are observed between the electrodes in all the anode structures. The powder plasma region is recognized in the schlieren patterns. A current filament is also formed between the anode plasma and the powder plasma. It is noted that there are three specific characteristics for the discharges with the non-plate anode. Firstly, the anode plasma region is larger and denser than that for the plate-plate discharge. Secondly, a pinched plasma column bridges between the anode plasma and the powder plasma. Thirdly, both the bright and the dark regions are observed near the cathode.



(a) Plate anode



(b) Conical tip anode



(c) Truncated conical tip anode with a hole

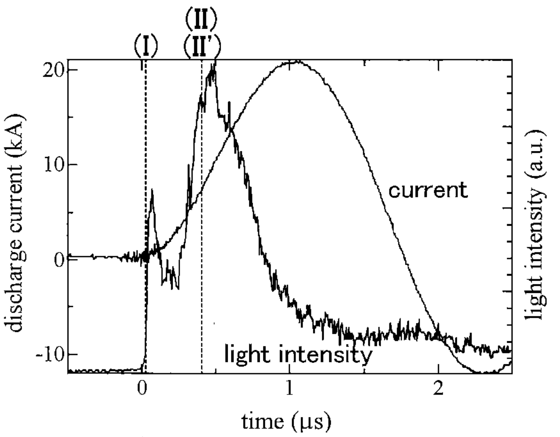


Fig. 7. Framing photographs taken for the three types of the anodes at the timing(I) and timing(II), schilielern patterns taken at the timing(II')

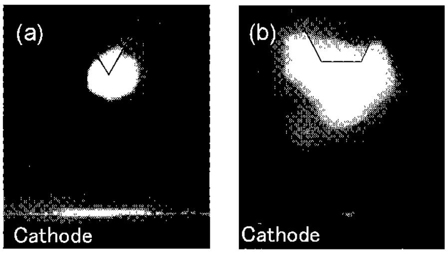


Fig. 8. Framing photographs of discharge without powder (a)conical tip anode and (b)truncated conical tip anode with hole in the timing(II)

5. Conclusion

The early stage of powder plasmas that influenced plasma development by pulsed high-current discharges was examined. The vaporization of the copper powder surface occurred as soon as the voltage was applied between the electrodes. These copper atoms play a significant role in the following discharge phase. The development of the powder plasma has different characteristics in comparison with vacuum sparks and conventional gas discharges because the spatial distribution of the initial matter entirely differs. The polarity effect of the electrode for the powder injection was observed. The formation of the anode plasma was suppressed by reducing the effective area of the anode. The powder plasma is a new method of producing plasmas. More experimental verifications are required to be used for the practical applications.

(Manuscript received June 2, 2003, revised Aug. 7, 2003)

References

(1) H.Nozawa, H.Ishihara, Y.Kawasaki, J.Kuroda, S.Ibuka, Y.Liu, K.Yasuoka, and S.Ishii : "High-Energy-Density Plasma Produced by Pulsed High Current Discharge of Powder", *Jpn. J. Appl. Phys.*, Part I, Vol.40, No.2B, pp.1009-1012 (2001)

(2) C. Masonnier, M. Haegi, and J. G. Linhart . Plasma Physics and Controlled Fusion Research II (IAEA, Vienna), p.345 (1966)

(3) S. S Valentin, A. M. Gennady, I. O. Vladimir, V. V Vladimir, and I. C. Lyudmila : "Current density and the specific energy input in fast electrical explosion", *IEEE Trans. Plasma Sci.*, Vol.27, pp.845-850 (1999)

(4) K.M.Chandler, D.A Hammer, D.B.S.Sinars, S.A.Pikuz, and T.A. Shelkovenko . "The Relationship Between Exploding Wire Expansion Rates and Wire Material Properties Near the Boiling Temperature", *IEEE Trans. Plasma Sci.*, Vol.30, pp.577-587 (2002)

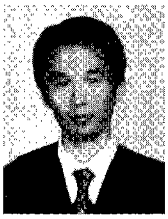
(5) A.Y.H.Cho . "Contact Charging of Micro-Sized particles in Intense Electric Fields", *J. Appl. Phys.*, Vol 35, pp.2561-1965 (1964)

(6) Ch K Erber, O.H.Herzog, A.Schulz, E.J Clothiaux, F Walden, and H-J.Kunze : "Optimization of micropinch plasmas produced by vacuum spark discharges", *Plasma Sources Sci. Technol.*, Vol.5, pp 436-441 (1996)

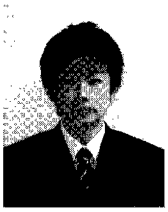
(7) N.V.Astrakhantsev, V.I.Krasov, and V.L.Paperny . "Ion acceleration in a pulsed vacuum discharge", *J. Phys. D : Appl. Phys.*, Vol.28, pp.2514-2518 (1995)

Takuma Yokoyama (Student Member) He was born on May 27, 1978. He received the B.E. and M.E. degrees from Tokyo Institute of Technology in 2001 and 2003, respectively. He is currentrly working toward the D.E. degree on phisics of microplasma at the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology.

Takuya Kuraoka (Member) He was born in 1977. He received the B.E and M.E. from Tokyo Institute of Technology in 2000 and 2002, respectively. He has joined East Japan Railway Company in the spring of 2002.



Kazuya Takano (Student Member) He was born on July 6, 1979. He received the B.E. degree from Ibaraki University in 2002. He is currently stydying as a Master course student at Tokyo Institute of technology.



Shinji Ibuka (Member) He was born on January 30, 1969. He received the B.E. and M.E. degrees from Tokyo Institute of Technology in 1992 and 1994, respectively. He is a Research Associate in the Tokyo institute of technology. His research interests have included high-voltage semiconductor switches and pulsed power technology.

Koichi Yasuoka (Member) He was born on September 22, 1955. He receive the M.E and D.E. degrees from Tokyo Institute of Technology, Japan, in 1980 and 1983, respectively. He is a associate professor in the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology. His current research interests include generation and utilization of atmospheric plasmas with DC and microwave technology.

Shozo Ishii (Member) He was born on December 16, 1945. He received the M.E. and D.E. degrees from Tokyo Institute of Technology, Japan, in 1970 and 1973, respectively. He is a professor in the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology. His research field includes plasma physics and high voltage engineering.