Pulse Generator for DLC Film-Forming

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Abstract

The pulse generator is a device that generates a momentary high power output. As for Meiden pulse generator, since the magnetic pulse compression circuit system is adopted, this pulse generator can offer stable high precision and a repeated power supply. As an example of an application, we conducted an experiment with Diamond-Like Carbon (DLC). The output characteristics of the pulse generator for this experiment were: output voltage of 30kV, output pulse width of 100ns or less, repetition frequency of 6kHz, and output energy of approx. 2J/pulse (average power: approx. 12kW).

1 Preface

The pulse generator is a device that generates a high pulse-state power in a very short amount of time at a level of microseconds or nanoseconds. Especially for a pulse generator generating a momentary power at a high voltage and high current, it is effective to use a circuit technology called a magnetic pulse compression circuit. This performs a time-based compression of a pulse with a very short rise time. This employs switching (using saturation characteristics of magnetic materials) and LC resonance. This pulse generator is used in a technical field called the "Pulsed Power[(1)]," which promotes wider applications. This paper introduces Meiden's pulse generator technology and the result of the film-forming test of the Diamond-Like Carbon (DLC)[(2)] as an example of its application.

2 Pulse Generator Technology

Meiden pulse generator uses a system by which energy stored in a capacitor is converted into a short pulse output at a rate of nanoseconds. This uses a semiconductor switch and a magnetic pulse compression circuit[(3)(4)]. The circuit configuration of the pulse generator and its operational principle are introduced below.

2.1 Pulse Generating Circuit Configuration

Fig. 1 shows the major circuit configuration of the pulse generator, which is composed of a semi-

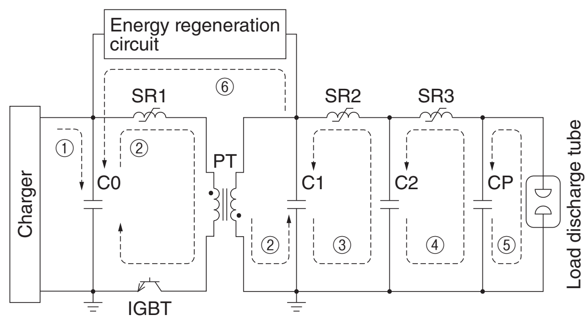

Fig. 1 Pulse Generating Circuit Configuration

The generating circuit configuration is shown. A short-pulse output is fed from the magnetic pulse compression circuit to the load. With the aid of an energy regeneration circuit, regenerated energy is charged at C0.

conductor switch, the Insulated Gate Bipolar Transistor (IGBT), a pulse transformer PT, saturable reactors SR1 ~ SR3, and capacitors C0, C1, C2, and CP. Magnetic materials of saturable reactors have a feature which shows very high permeability in the low-current unsaturated zone, but after that, the current is increased and the magnetic flux attains the magnetic saturation level; there is almost no increase in the magnetic flux. Due to such characteristics, when a voltage is applied to the saturable reactor, it functions as a large inductance while the current is small and it puts a curb on the current change. If the current exceeds a certain threshold level, however, its inductance becomes small and it functions like an air-core reactor and the current increases suddenly. For this reason, by combining capacitors and switching characteristics which two inductances are switched depending on the current level, it is possible to perform compression of a pulse as shown in the schematic diagram in **Fig. 2** and a pulse compression can be performed as described below.

2.2 Operational Principle of Pulse Generating Circuit

(1) Using a charger, C0 is charged at a specified voltage through a current path indicated by the dotted line ① in **Fig. 1**. While this capacitor is being charged up, the saturable reactor provided with a secondary winding is made to stay in the initial magnetization state by giving a bias magnetic field to this winding, although this scheme is omitted in **Fig. 1**.

(2) When IGBT in **Fig. 1** is turned on for a specified time, the charging current is fed from C0 to C1 on PT secondary side through SR1 and PT as indicated by the dotted line ②. While SR1 is unsaturated at that time, a current increase is still small and the C1 voltage rises slowly. When saturation is reached at SR1, the current increases suddenly and the charging voltage characteristic becomes just like an air-core reactor and a capacitor; thus, the voltage decreases as low as −30kV in **Fig. 2**.

(3) Current of the dotted line ③ flows into SR2 at the next stage. However, even when the V_{c1} voltage rises, the SR2 firstly stays in the unsaturated zone and the current increases slowly. When V_{c1} reaches saturation at the time of −30kV, the current increases suddenly and C2 begins to charge up rapidly. If saturation inductance of SR2 has been made to be smaller than that of SR1, however, the resonance period of SR2 and C2 becomes shorter than that of SR1 and C0. As a result, a short-time voltage pulse like V_{C2} is generated.

(4) Likewise, when one more stage is produced with SR3 and CP, pulse compression is performed as indicated by the dotted line ④ and CP gains a voltage of extremely short-time pulse of 100ns or less.

(5) Due to a pulse voltage generated at CP, a high voltage appears between the electrodes of the load discharge tube and discharging is performed as indicated by the dotted line ⑤. Although this is omitted in **Fig. 2**, if the load is of low impedance, surplus energy not absorbed in the load during this discharge time returns to CP as a result of polarity reversal. Maintaining resonance, this energy flows back through the pulse compression circuit and returns as far as C1.

(6) As indicated by the dotted line ⑥, energy is regenerated at C0 through the energy regeneration circuit. Since surplus energy is reused as a result of energy regeneration, efficiency is improved and it is possible to prevent the occurrence of abnormal operation such as another discharge caused by recharging at the CP.

The pulse generator operates, following the course of (1) to (6) above. It performs this operation at a high repetition frequency. In case of compression as shown in **Fig. 2**, the output pulse width is 100ns or less, output voltage is −25kV, and repetition frequency is 6kHz.

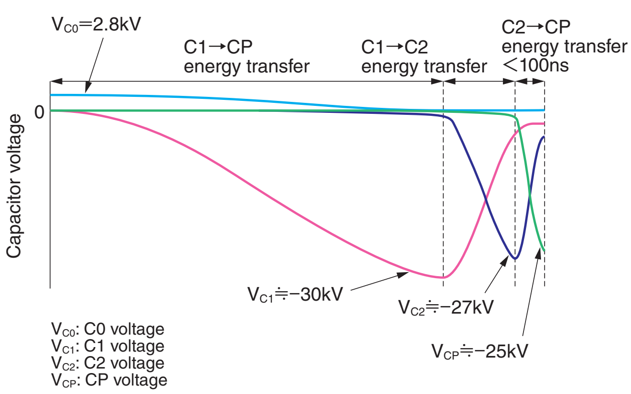

Fig. 2 Operating Waveforms of Pulse Generating Circuit (Schematic Diagram)

A schematic diagram of pulse compression performance is shown with the function of a pulse generator circuit (C0→CP energy transfer).

3 Pulse Generator for DLC Film-Forming Experiment

3.1 What is DLC?

The DLC is a kind of a hard film that is an amorphous carbon film in a core structure of carbon atoms consisting of both sp^3 bond of diamond and sp^2 bond of graphite. **Fig. 3** shows a ternary phase diagram of an amorphous carbon film composed of sp^2 bond, sp^3 bond, and hydrogen. The hardness above 10Gpa is generally called the DLC.

The DLC possesses physical properties of both diamond and graphite. It is so-called “moderate” material. Since a variety of physical properties and features can be created by proper mixing, this material has been widely distributed as a coating material for mechanical parts. **Fig. 4** shows typical features of the DLC and an overview diagram of applications.

3.2 DLC Film-Forming Method

Fig. 5 shows the method of DLC film-forming and conceptual diagram. For DLC materials, many film-forming methods have been proposed; however, each method calls for the three essential factors of “raw material,” an “energy source,” and a “reactor (reaction furnace).” As a raw material, we use a gaseous body (methane, etc.) or a solid body (graphite, etc.) and such material contains carbon. As an energy source, electric discharges by an RF generator or a pulse generator are used to ionize the raw material. As a reactor, discharge electrodes or the like installed in a chamber are used. DLC film-forming is given to a substrate located inside the reactor.

Here, when a pulse generator is used as an energy source, it is possible to achieve the DLC film-forming with the following features:

(1) DLC film-forming is possible at an atmospheric or quasi-atmospheric pressure.

(2) It is hard to result in arc discharges, and therefore defects may be few.

(3) Film-forming can be made at a low temperature. The selectivity of substrates can be extended.

In the following paragraph, the pulse generator used for experiments will be introduced.

3.3 Pulse Generator for DLC Film-Forming Experiment

Table 1 shows the major specifications of the pulse generator for DLC film-forming experiments. Fig. 6 shows an external appearance of the pulse generator. This generator gains a power input of 3-phase 200V. It can generate output pulses specified for an output voltage of 30kV (negative polarity), output pulse width of 100ns or shorter, and a repetition frequency of 6kHz (6000 pulses per second). Its output energy is approximately 2 joules per pulse. Average power output is 12kW and peak power during pulse output amounts to approximately 20MW.

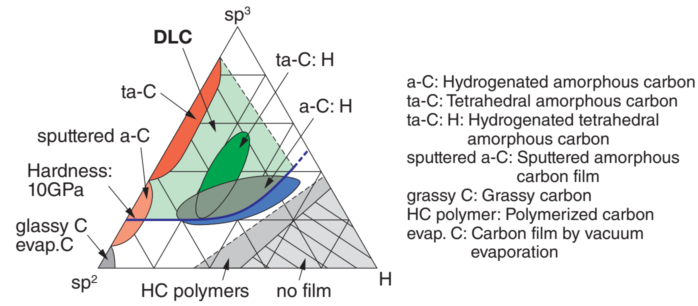

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Fig. 3 Classification of Amorphous Carbon Films

Classification of amorphous carbon films is shown with a ternary phase diagram of sp^2 bond, sp^3 bond, and hydrogen.

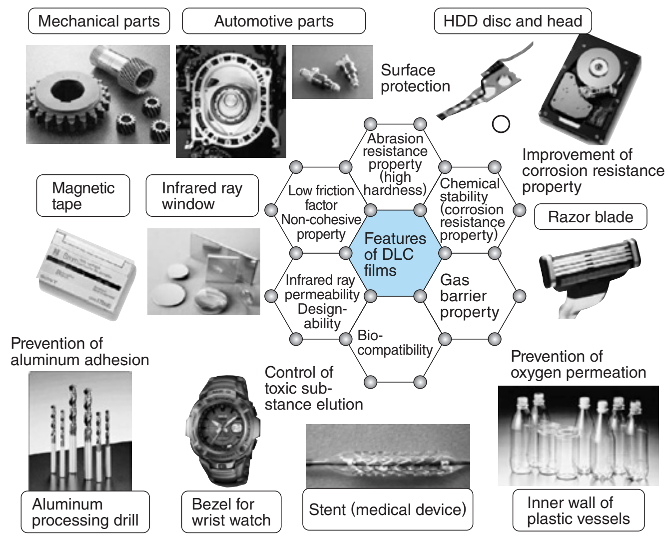

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Fig. 4 Features of DLC and Overview Diagram of Applications

Physical properties of DLC, functional features, and examples of applications are shown.

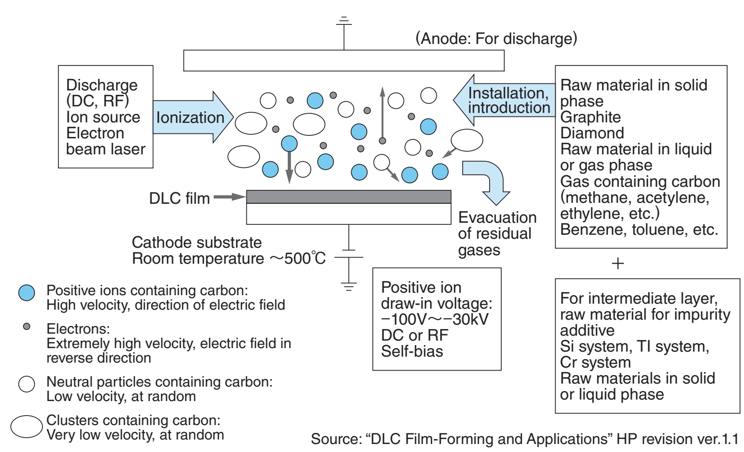

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Fig. 5 Method of DLC Film-Forming and Conceptual Diagram

A conceptual diagram of DLC film-forming method is shown. A material containing carbon is led in between discharge electrodes and a DLC film is formed on a substrate by coating through ionization from the energy source.

Table 1 Specifications of Pulse Generator for DLC Film-Forming Experiments

Specifications of pulse generator for DLC film-forming experiments are shown.

Item	Specified values
Input power source	3-phase, 200V, 50/60Hz
Output voltage	≦30kV (Negative polarity)
Output pulse width	≦100ns
Repetition frequency	≦6kHz
Output energy	Approx. 2J/pulse
Average power output	Approx. 12kW
Peak power	Approx. 20MW
Dimension	W900 × H1700 × D800mm
Cooling system	Water-cooling

Fig. 6 Pulse Generator for DLC Film-Forming Experiments

An external appearance of the pulse generator is shown.

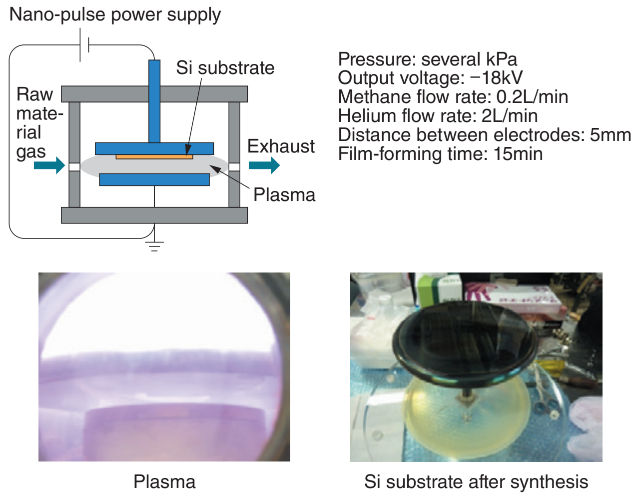

Fig. 7 Testing Equipment for DLC Film-Forming and Testing Conditions

Test equipment for DLC film-forming and testing conditions are shown.

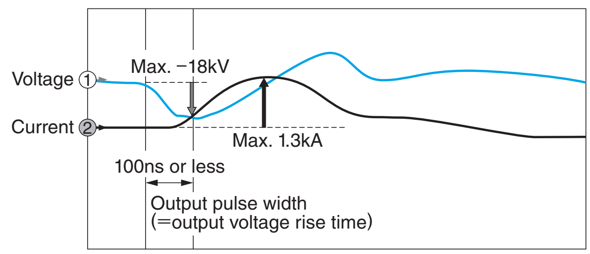

Fig. 8 Waveforms of Pulse Generator Output (Discharge Waveforms)

Waveforms of pulse generator power output are shown, observed during the experiment of DLC film-forming.

4 DLC Film-Forming Experiment

In this chapter, the result of DLC film-forming experiments will be introduced[5]. These experiments were conducted in collaboration with Prof. Naoto Otake of Tokyo Institute of Technology, by using the use of the pulse generator introduced in foregoing paragraphs. In particular, the aim of such experiments was to realize the large size DLC film-forming by taking advantage of high voltage and high current offered by Meiden pulse generator.

4.1 DLC Film-Forming Experiment Testing Unit and Testing Conditions

Fig. 7 shows an outline of testing equipment and conditions. In this case, DLC film-forming experiment was conducted by the Chemical Vapor Deposition (CVD) method under low pressure (several kPa). The testing chamber is a cylindrical vessel in a size of 200mm in diameter by about 300mm in length. Opposing electrodes of 150mm in diameter were installed at a separation of 5mm and pulse power shown in Fig. 8 is applied. A raw material gas of methane is fed for 15 minutes to generate plasma for the formation of a film on a Si substrate.

4.2 Result of DLC Film-Forming Experiment

Fig. 9 shows a Raman spectrum of DLC film obtained from experiments. This spectrum consists of two broad peaks of Band G (Graphitic) in the proximity of 1580cm^{-1} and Band D (Disordered) near 1250cm^{-1}. This fact suggests that the synthetic film consists of DLC. This DLC film was formed in a large area on the Si substrate and electrodes of 150mm in diameter. The result of observation of the Raman spectrum at various points of the film sug-

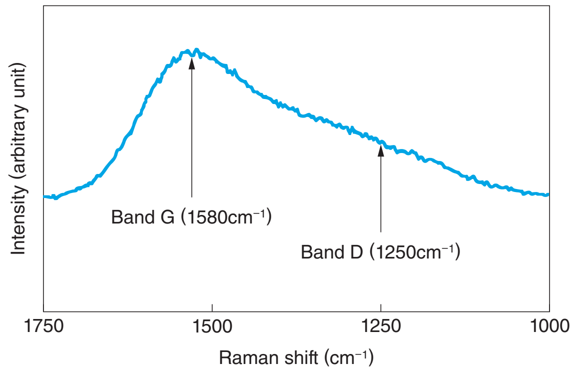

Fig. 9 **Raman Spectrum of DLC Film**

Raman spectrum of DLC film is shown, obtained from experiments.

gests that there is an outstanding issue, i.e., non-uniformity. Going forward, we will improve the electrode structure, gas flow path, and other factors to obtain uniform films.

In addition, the hardness of DLC films was measured through the nano-indentation test. The result indicates that the hardness is 14GPa or more, and this verifies that the obtained DLC film had a sufficient amount of hardness.

5 Postscript

This paper introduced our pulse generating technology and some examples of applications with the result of DLC film-forming experiments. In addition to some examples of applications introduced in this paper, the pulse generator is useful in a variety of industrial fields such as waste gas treatments, water processing, and many others. We expect that the application range of this product will be extended further. We will make every effort to increase various product offerings to increase the applications of our products.

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