SUBSTRATE BIAS EFFECT ON CRYSTALLINITY OF POLYCRYSTALLINE SILICON THIN FILMS PREPARED BY PULSED ION-BEAM EVAPORATION METHOD

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ABSTRACT

The deposition of polycrystalline silicon thin films has been tried by a pulsed ion-beam evaporation method, where high crystallinity and deposition rate have been achieved without heating the substrate. The crystallinity and the deposition rate were improved by applying bias voltage to the substrate, where instantaneous substrate heating might have occurred by ion-bombardment.

1. Introduction

Polycrystalline silicon (poly-Si) thin films are widely used in various electronic devices such as thin film transistors, solar cells, peripheral circuits of liquid-crystal displays and electrodes in silicon integrated circuits because of high optical absorption and high carrier mobility.\(^1\)\(^-\)\(^3\) Generally, these thin films have been fabricated by a plasma-enhanced chemical vapor deposition (PECVD) method using highly hydrogen-diluted SiH\(_4\). It is well known that poly-Si thin films deposited by PECVD need post annealing or substrate heating, and that the deposition of these thin films are desired at low temperatures.

In practical application such as solar cells, the very low deposition rate is a serious problem for achieving higher throughput of the devices. For this purpose, several types of low-pressure and high-density plasma sources have been applied to increase the crystallinity and the deposition rate of poly-Si thin films. They are represented such as inductively coupled plasma (ICP), surface wave plasma (SWP), ultra high-frequency plasma (UHF) and electron cyclotron resonance plasma (ECR).\(^4\)\(^-\)\(^7\)

A novel thin film preparation method called pulsed ion-beam evaporation (IBE) has been proposed by one of the authors, where various thin films have been prepared successfully.\(^8\)\(^-\)\(^9\) By IBE, crystallized thin films, such as B\(_4\)C, BaTiO\(_3\), BN, SiC, SrAl\(_2\)O\(_4\) and TiFe were...
prepared without heating substrates. Only preliminary results were reported on the preparation of poly-Si thin films by IBE. In the previous paper, we have reported about substrate bias effect on the crystallinity of poly-Si thin films. It was found that a large-area, high crystallinity poly-Si thin film could be achieved by applying bias voltage to the substrate. In this paper, we report the deposition of poly-Si thin films at room temperature, i.e., without substrate heating or annealing, by using the intense, pulsed, ion-beam evaporation (IBE) technique. To investigate the crystallization and deposition rate, the substrate was placed at r=10mm away from the plasma center. Furthermore, to study the crystallinity, bias voltage was applied to the substrate.

2. Experimental Apparatus and Method

Figure 1 shows the schematic of the experimental arrangement. An intense, pulsed, light ion-beam (LIB) generator “ETIGO- II” at the Nagaoka University of Technology was used. A high-voltage pulse from “ETIGO- II” was applied to a magnetically insulated diode (MID), and an intense pulsed light ion-beam was extracted. The beam hits the target, producing high-density ablation plasma, which was deposited on the substrate placed parallel to the target at a certain distance. The ion beam used was the peak energy of 1 MeV, the pulse width of 50 ns, and the energy density on the target of 50 J/cm². The beam spot size on the target was typically 20mm in diameter.

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<th>Table I Typical experimental conditions</th>
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<td>Main component of ions</td>
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<td>Beam voltage (peak)</td>
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<td>Diode current</td>
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<td>Energy density on target</td>
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<td>Anode-Target distance (d_AT)</td>
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<td>Substrate temperature</td>
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<tr>
<td>Number of shots</td>
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<td>Substrate bias voltage (V_{bias})</td>
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Fig. 1 Experimental setup.
We used single crystal silicon with $50 \times 50 \times 10$ mm in size as a target. As a substrate, we used single crystal silicon wafer (100). The substrate ($15 \times 20 \times 1$ mm) was kept at room temperature and the ablation plasma directly hits the substrate. The poly-Si thin films were deposited under a pressure of $\sim 10^{-4}$ Torr. The bias voltage was applied to the substrate placed 70 mm away from the target. Between the target and the substrate a firm insulation was carried out to avoid the current flow and to stand the potential difference. Typical experimental conditions are presented in Table I.

In this study, we examined the crystal structures of the obtained poly-Si thin films by X-ray diffraction (XRD, RIGAKU, RINT 2000°). The grain size was estimated from the full width at half-maximum (FWHM) values of (111) peak in the XRD spectra by using Scherrer's formula. The film thickness ($d$) was estimated from the scanning electron microscope (SEM, JEOL, JSM-6700F) morphology. The crystallinity of the thin film was measured by Raman spectroscopy and the excitation source consisted of an argon-ion laser tuned at 514.5 nm, releasing 200 mW to the sample. Raman scattering was collected at right angles, dispersed with a double spectrometer (JASCO, NR-1100). The crystallinity of the Raman spectra ($\rho$) was defined as the following equation, where $I_c$ and $I_a$ are the intensities of the polycrystalline phase (520 cm$^{-1}$), and the amorphous phase (480 cm$^{-1}$), respectively. In the XRD spectra, $I_c$ and $I_a$ are the intensities of the sharp crystalline peak and the broad amorphous ones respectively, which is written by

$$
\rho = \frac{I_c}{I_c + I_a}
$$

3. Experimental Results

3.1 XRD Analysis

Figure 2 shows XRD spectra of poly-Si thin films deposited on silicon substrates at various substrate bias voltage ($V_{\text{bias}}$). XRD spectra revealed that the poly-Si phases are varied while applying $V_{\text{bias}}$ to the substrate. It was noticed that at $V_{\text{bias}} = -50$ V, all peaks have considerable high intensities than other $V_{\text{bias}}$ conditions. From the XRD spectra it was also revealed that the crystallinity of the thin films is improved by applying bias voltage to the substrate. However, at $V_{\text{bias}} = -100$ V, the XRD peak intensities showed a decreasing trend.
3.2 SEM Analysis

Figure 3 is the SEM image of poly-Si thin films deposited on silicon substrates at various bias voltage ($V_{bias}$). In Fig. 3, we have evaluated the film thickness. We see that the film thickness is increased at $V_{bias} = -50$ V compared with that $V_{bias} = 0$ V. This result agrees with our previous experiments. When the $V_{bias}$ is increased to $-100$ V, the thickness of the film was found to decrease compared to $V_{bias} = -50$ V. When bias voltage was applied to the substrate it was also noticed that the considerable density of the thin film has been improved.

$$
V_{bias} = 0 \text{ V, } d=1.06 \mu \text{ m} \quad V_{bias} = -50 \text{ V, } d=1.33 \mu \text{ m} \quad V_{bias} = -100 \text{ V, } d=1.06 \mu \text{ m}
$$

Fig. 3  SEM images at various substrate bias voltage.
3.3 Raman Analysis

The Raman spectra are shown in Fig. 4. The graph where $V_{\text{bias}} = 0$ V is found to contain some amorphous phase, which exhibits a broad peak at 468 cm$^{-1}$. The crystallinity phase at 520 cm$^{-1}$ has increased by using $V_{\text{bias}} = -50$ V, but a slight decrease at -100 V was observed. The enhancement of crystallinity at $V_{\text{bias}} = -50$ V has been found in XRD analysis as well.

![Fig. 4 Raman spectra at various substrate bias voltage.](image)

4. Discussions

The crystallinity index of the prepared thin films was calculated using the XRD and Raman spectroscopy data, which are shown in the following Figs. 5 and 6. According to Figs. 5 and 6, the increase in the crystallinity is observed by applying substrate bias voltage. On the other hand, the values are found to decrease at $V_{\text{bias}} = -100$ V. The influence of the substrate bias voltage may be explained using the following approach. With increasing negative $V_{\text{bias}}$, the energy of the attracting ions towards the substrate is increased, and as a result, the surface is heated and resputtering takes place. Since the temperature of the substrate surface is increased due to ion-bombardment, some disorder may result within the thin film.

![Fig. 5 XRD Crystallinity spectra as a function of substrate bias voltage.](image)
Since the ion-bombardment could be considered to substrate heating during deposition, grain size growth might also give an explanation to crystallization. In Fig. 7, evaluated grain size from the XRD spectra is given. We have achieved a good crystallinity at $V_{\text{bias}} = -50$ V (Fig. 5 and 6) and at the same time the grain size was noted to be increased at this point. The instant substrate heating with the use of bias may have resulted to crystallize, giving the increase in the grain size.

The deposition rate calculated from $d$ in Fig. 3 as a function of bias is shown in Fig. 8. Here, we have succeeded in the achievement of a high deposition rate of $\sim 270$ nm/shot with using the substrate bias voltage. It has been seen that the deposition rate has gradually increased with increasing $V_{\text{bias}}$ at various distances, but that it decreases at $V_{\text{bias}} = -100$ V. This was contrary to expectations, since it was anticipated that with increasing the negative $V_{\text{bias}}$, will increase the energy of the attracting ions towards the substrate, i.e. the ion-bombardment energy and as a result the surface will be heated to allow resputtering to take place. This could be a factor for the decrease in the film thickness as we increase the negative bias of the substrate.
The increase in the film thickness with substrate bias voltage can be explained but the main mechanism behind is still unknown. When the substrate bias voltage is zero, there is no external influence to the ablation plasma plume and the particles are deposited on the substrate without any interference. On the other hand, if we supply electric field to the existing ablation plasma the particles present in the plume experience some effects in them. For example, applying negative bias to the substrate means that the positive ions present in the plume get attracted towards the substrate, resulting in drag for the neutral particles. This phenomenon is assumed to have increased the film thickness where, the ion drag force is considered to take place in the bias field. [15]

5. Summary

Using intense pulsed ion-beam evaporation technique, we have succeeded in the preparation of polycrystalline silicon thin films. The grain size variation was noted by changing the bias conditions. The crystallinity and the deposition rate of poly-Si thin film have improved by applying bias voltage to the substrate, which may have contributed to instantaneous substrate heating to take place from the ion-bombardment energy.

References


PULSED POWER LASER RADIATION EFFECTS ON
MYCOPLASMA AGALACTIAE

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ABSTRACT

The biological effects of the laser radiation emitted by the Nd:YAG laser (second harmonic, wavelength 532 nm / fluence 32 mJ/cm\textsuperscript{2} / pulse duration 6 ns) on the Mycoplasma agalactiae bacterium were studied. The radiation was found to intensify the multiplication of the bacteria irradiated in TRIS buffer (0.125 M), without however affecting the proteinic composition of the cell membrane. When the bacteria were irradiated in their growth medium (PPLO, broth) being later cultivated on a solid medium (PPLO agar), the exclusive presence of the atypical colonies (granular and T-like ones) was noticed.

1. Introduction

There is knowledge of experimental bacteria irradiation with X rays, alpha, beta and gamma radiations, as well as with fast neutrons; the cultures used were those of Staphylococcus aureus, Salmonella typhimurium, Escherichia coli, Bacillus pyocyaneus, Bacillus anthracis, Serratia marascens, etc. The major effects were either bactericidal (as an inhibition process of the cell proliferation), or radioprotective (whenever the radioprotective substances reduce the toxic ones resulted from the irradiation disintegration). The differences between the effects of the ionizing and ultraviolet waves irradiation were not too great\textsuperscript{1}).

Ones the lasers were developed, a series of experimental researches were conducted on the laser radiation effects on biological media \textsuperscript{2,3,4,5}) a limited number of reports on the laser radiation-bacteria interaction should also be mentioned \textsuperscript{6,7,8,9}). Many experimental results confirm the laser radiation to be able to change the cell proliferation processes and induce important structural changes \textsuperscript{7,9}). The effects of the laser radiation on the pro- and eukaryote cells are conditioned by certain parameters such as the wavelength, the power and energy level, monochromaticity and irradiation duration.

Our aim was to study the laser radiation (532 nm, green in color) effects on Mycoplasma agalactiae, a bacterium of the Mollicutes division, Mycoplasma genus; the bacteria belonging to this genus lack the rigid cellular wall and have elastic cytoplasmatic
membrane. A vaccinal *Mycoplasma agalactiae* strain (Pasteur Institute, Bucharest) was irradiated.

The bacteria were irradiated both in their growth medium and in TRIS buffer (0.125 M), and then studied for the cell morphology (by electron microscopy), the cell membrane protein composition (by sodium dodecyl sulfate polyacrylamide gel electrophoresis, SDS-PAGE) and the cultivability of the bacteria irradiated in their growth and then reinoculated into a solid medium.

2. Material and method

2.1. Irradiation

The radiation source was made of a solid state Nd:YAG laser that operated at 532 nm in green. The other experimental parameters were:

a) The laser fluence (laser energy/irradiated area) : 32 mJ/cm²;

b) The laser pulse duration τ = 6 ns;

c) The laser pulse repetitive frequency ω = 0.5 Hz;

d) The laser pulse number N = 300.

Throughout the irradiation, the samples were homogenized on a magnetic stirrer.

2.2. Irradiated samples

The 48 hour old *Mycoplasma agalactiae* culture in PPLO broth (Difco): 600 ml of the basic medium (PPLO, Difco), 20% liquid yeast extract (LYE), 20% horse serum, 1% glucose, 400 IU/ml of penicillin, 0.05 g% thallium acetate and 12 ml of phenol red solution.

a. The culture was incubated at 37°C and 1400 rpm under agitation, the density was 1x10⁶ CFU/ml and 4 ml were subjected to the irradiation. Following irradiation, 0.1 ml of the culture was seeded into the solid medium: PPLO agar (Difco) supplemented with 20% LYE, 20% horse serum, 1% glucose, 400 IU/ml of penicillin, 0.05 g% thallium acetate. The Petri plates were incubated at 37°C and daily examined for 5 days.

b. The bacterial bodies suspended in TRIS buffer (1x10⁹ CFU/ml): the 48 hour old *Mycoplasma agalactiae* culture was centrifuged at 4°C and 13,000 g for 35 minutes. The pellet was washed 3 times in TRIS buffered solution (0.01 M TRIS-HCl, 0.1 M NaCl, pH 7.2) and once in 0.125 M TRIS-HCl buffer, pH 6.8. The final sample concentration was adjusted to 1x10⁹ CFU/ml in 0.125 M TRIS-HCl buffer, and 4 ml were subjected to the irradiation.

2.3. SDS-PAGE

The SDS-PAGE was performed as described by Laemmli with 10% separation gel. The samples (the irradiated in 0.125 M TRIS-HCl buffer and the non irradiated one) and the molecular weight standard (Sigma) were dissolved in standard buffer (0.05 M TRIS-HCl, pH 6.8; 2.5% SDS; 5% 2-mercaptoethanol; 15% glycerol; 0.05% bromphenol blue) and then heated in a water bath (100°C) for 5 minutes. The insoluble material was removed by centrifugation at 10,000 g for 10 minutes. The solubilised cellular proteins and standards were electrophoresed (Mini Protean II, Bio-Rad) at a constant current, 200 V (Power-Pac 300, Bio-rad).
2.4. Electron microscopy

The samples were examined under a transmission electron microscope (EM 125, 75 kV acceleration voltage, 6,000-400,000 x magnifying power) using the direct negative contrast method. Each sample was placed on 150 mesh grids and electron contrasted using a 2% alcohol solution of phosphotungstic acid, pH 7.4 as the contrast substance.

3. Results

The irradiation affected the cultural characters of the bacteria on the solid medium. Thus, atypical colonies were found 72 hours after the cultivation of the irradiated samples: they were granular and punctiform, T-like (Figure 2). The nonirradiated control exhibited both typical, fried eggs-like colonies, and atypical ones (Figure 1).

Electrophoresis did not evidence differences among the irradiated and non irradiated samples as to the proteinic bands aspect (Figure 3), while electron microscopy showed no significant differences with the samples irradiated in their growth medium in comparison with the non irradiated ones examined under the same conditions.

Significant differences were, however, found with the irradiated TRIS buffer sample as against the nonirradiated control, whose cells exhibited monomorphism: cells clumps were noticed, and the cells were round ranging between 80 and 100 nm (Figure 4).

Fig. 1 72 hour *Mycoplasma agalactiae* culture irradiated on PPLO agar.

a. Atypical, granular colonies.

b. Atypical, T-like punctiform colonies.
Fig. 2 Nonirradiated *Mycoplasma agalactiae* culture on PPLO agar.

a. Typical colonies.
b. Atypical, granular colonies.
c. Atypical, T-like punctiform colonies.

Fig. 3 Electrophoresis on irradiated *Mycoplasma agalactiae*.

Fig. 4 Nonirradiated *Mycoplasma agalactiae*: TRIS-HCl (0.125 M) buffered germs suspension. Round cells with monomorphism.
As for the samples irradiated in TRIS buffer, the cells are characterised by a marked polymorphism: ring-like forms (Figure 5), glove fingers-like ones (Figures 6) and reniform aspects (Figure 7) were noticed. All these exhibited a rise in the cell volume and filamentous protrusions-like formations. In our opinion, these formations are not mere membranaceous prolongations; they are daughter cells resulted from cellular division processes, either by means of filamentous formations (Figure 3) or by budding (figure 3 and 5). The lack of the cell wall allows the genetic material of these daughter cells to be visualized.
These findings permit the assumption that, under the laser radiation influence, the intracellular metabolic processes are intensified and accompanied by more marked bacterial division processes in a neutral medium.

Due to the lack of the rigid cell wall, mycoplasmas have a marked morphologic plasticity dependent on the medium in which they were grown. The changes in the form found in the irradiated cells of our experiment do not exist in the nonirradiated controls. We can, therefore, state that the laser radiation is responsible for the changes induced to the irradiated samples, i.e. the increased cell volume and morphological plasticity, the presence of the division processes.

4. Conclusions

1. The influence of the Nd:YAG laser radiation second harmonic, (wavelength 532 nm / 32 mJ/cm² / 6 ns) on the *Mycoplasma agalactiae* bacterium was studied.

2. The laser radiation affected the TRIS-HCL buffered bacterial suspension by increasing the cellular volume and the morphologic plasticity, and by intensifying the metabolic processes translated by cell division processes.

3. The laser radiation did not morphologically affect the bacteria irradiated in their growth medium, it merely affected the cultivability degree on a solid medium.

4. The laser radiation did not affect the proteinic composition of the irradiated bacteria cell membrane.
References

CHARACTERISTICS OF A HIGH-CURRENT PULSE GLOW DISCHARGE

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ABSTRACT

The voltage-current characteristics of transient glow discharges in dry air (N₂:O₂=8:2) at pressure of 10 torr were obtained for discharge currents up to 150 A using parallel-plane electrodes. The time-dependent glow voltage is obtained accurately by solving the circuit equation using the measured values of the current and breakdown voltage. Carborundum damping resistor is altered from 1 to 200 Ω in order to obtain the voltage-current characteristics in a wide current range. The glow discharge voltage was almost constant until the whole surface of the cathode was covered with glow, i.e., until the discharge current became 3.7 A under our experimental condition (a normal glow discharge mode). The voltage, however, increased with the current when the glow covered over the cathode (an abnormal glow discharge mode). The electron density in positive column of the high-current glow discharge were obtained to be 4.9x10¹¹ cm⁻³ from calculation based on nitrogen swarm data. This value is close to the electron density 3x10¹¹ cm⁻³ measured with Langmuir probe. The glow-to-arc transition starts to develop in the discharge region near the cathode at 0.035 J·cm⁻³ energy dissipated in the cathode fall region during the glow phase. The high-current glow discharge plasma was successfully produced with 35 μs duration at 1 kHz repetition rate using a pulse modulator.

I. Introduction

Glow discharges are used for material surface treatment as metal nitriding, ion implanting to polyethylene etc. Although the low pressure glow plasma are mainly used in conventional system for nitriding and implanting, some nitriding are operated in a range of a few torr. Our objective is the production of a high density, large volume and low gas temperature plasma utilizing a pulse glow discharge with high-current at gas pressure from a few torr to a hundred torr. A lot of processes in a direct current (dc) glow plasma are governed by the voltage-current (V-I) characteristics of the discharge. In this paper, the experimental studies on the V-I characteristics of a transient or pulsed glow discharge with high current up to 150 A after static breakdown of pure nitrogen gas are described. Using the measured glow voltage and the cathode fall voltage, the electron density and the electron temperature in the positive column are calculated.

II. Experimental details

The experimental apparatus used in the present experiment consists of a co-axial discharge chamber, damping resistors and a capacitor. Electrode plates with rounded edges were made of copper and set in the discharge chamber. The overall diameter and thickness of the
electrodes are 10.7 cm and 1.5 cm, respectively. The one electrode is connected to a 1.89 \textmu F capacitor which is charged negatively up to high voltage. The other electrode is grounded through the damping resistors. The gap spacing between the electrodes was changed from 0.2 to 2 cm. The pressure of pure nitrogen gas was kept to 10 torr in the discharge chamber. The gas in the chamber was exchanged after every discharge.

The 1.89 \textmu F capacitor was slowly charged with nearly constant current of 0.5 mA. The carborundum damping resistors were used to control the discharge current. The return current flows into the ground through twelve stainless rods. The breakdown voltage was accurately measured using a resistive voltage divider with 1000:1 ratio. The discharge current was measured by means of a Pearson Model 110A current transformer and a Sony-Tektronix Model 540 digital oscilloscope. Then the signal is transmitted to a personal computer through a GPIB cable in order to calculate the gap voltage \( v(t) \) using the following circuit equation:

\[
v(t) = V_{br} - \frac{1}{C} \int i(t) dt - R \cdot i(t) - L \frac{di(t)}{dt},
\]

where \( V_{br} \) and \( i \) are the breakdown voltage and the current, respectively; \( C, R \) and \( L \) are the capacitance, resistance and inductance of the circuit, respectively. The inductance \( L \) was determined from a period of the \( L-C \) oscillation in the prior experiment. The damping resistor \( R \) was altered from 1 to 200 \( \Omega \) to acquire the \( V-J \) characteristics in a wide current range.

Electron density and temperature was obtained using Langmuir probe. The measurement of the probe current waveforms in pulsed glow plasma at various probe bias voltages, and probe current-bias voltage curves were drawn using them at various times. The probe tip is made of tungsten with 0.2 mm diameter and 3 mm length, and is placed at the middle between the electrodes.

Fig. 1 Experimental apparatus. Fig. 2 Equivalent circuit of the discharge system.
III. Characteristics of a transient glow discharge

A. Voltage-current characteristics of transient glow discharge

Figure 3 shows a typical current oscillogram and the series of photographs of high-current transient glow discharge, respectively. The exposure time, i.e. the time duration between the converter camera is opened by the gating pulse and closed, is 50 ns. The converter opening time for each frame is indicated by the number enclosed with a circle under the trace of the discharge current. The time \( t \) is measured from the origin when the discharge current is first detected, and the time \( t_s \) indicates the beginning of the filamentary glow or arc discharge. The structure of the discharge during the development can be deduced from the series of photographs in Fig. 3. The appearance of the discharge shown in frame ① closely resembles that of a stable glow discharge exhibiting a uniform positive column, a Faraday dark space and a negative glow. Frames ④-⑧ show that after the time \( t_s \) show that appears on the surface of the cathode a luminous spot and induces the second glow phase and/or the arc phase. With the increase in current, the discharge constricts while the luminosity increases at the core of the discharge.

The build-up of the current takes place in two steps as shown in Fig. 3. In the growth of the discharge current up to the order of amperes, it has been reported that three plateaus appear corresponding to the occurrence of the diffused glow, the filamentary glow, and the arc in hydrogen in pressure range from 300 to 700 torr at electrode separations of several millimeters. 9) In this work, the step of the current growth according to the filamentary glow cannot be distinguished from that of the arc discharge. The duration of the glow phase and the glow current are 2.2 \( \mu \)s and 310 A, respectively.

![Fig. 3 Shutter photographs of a discharge at 5.5 torr and 2 cm. Shutter opening time for each frame is indicated under the trace of the discharge current. Lower electrode is cathode and upper electrode is anode.](image)

Representative voltage and current waveforms of high-current transient glow discharge at damping resistor of 1 \( \Omega \) are shown in Fig. 4. After a static breakdown, marked ① on the trace, the discharge current increases up to 150 A, and the gap voltage decreases from a breakdown voltage to the value of a quasi-stable step, marked ②, as the discharge develops. The time duration from ② to ⑤ indicates that the discharge mode is the transient glow. In this case, the glow voltage decreases from 920 V to 800 V with decreasing glow current from 150 A to 107 A. At the time marked ③, an appearance of a luminous spot on the cathode
surface was observed by the image-converter camera photographs. After then the voltage collapses to a few ten volt with glow-to-arc transition in time from ③ to ④. After the time marked ④, the arc discharge current decreases at a time constant of RC.

Figure 5 shows the $V$-$I$ characteristics obtained from Fig. 4. The $V$-$I$ characteristics have two positive slopes; the first is the time from ② to ③ and the second is the time after ④. These correspond the characteristics of the glow discharge and the arc discharge, respectively. The two negative slopes mean the transient phases; Townsend-to-glow transition (①$\rightarrow$②) and glow-to-arc transition (③$\rightarrow$④).

![Fig. 4 Voltage and current waveforms of the pulse discharge. $P=10$ torr. $d=1$ cm. $R=1\Omega$.](image)

![Fig. 5 Voltage-current characteristics of the pulse discharge. $P=10$ torr. $d=1$ cm. $R=1\Omega$.](image)

Figure 6 shows the $V$-$I$ curves of the glow mode at various values of the resistance $R$ of the damping resistor. The broken line shows the interpolation by an exponential function. In the case of $R=1, 3, 9\ \Omega$, the glow discharge is transient, which means glow-to-arc transition occur after the glow. In this case, the duration of glow are 3.5, 3.0, 20 $\mu$s, respectively. When $R > 18\ \Omega$, the glow-to-arc transition does not occur, therefore the glow mode durations are almost determined by the time constant $CR$ ($=1.89\ R\ [\mu s]$) of the apparatus. The empirical formula of current density $j_{ng}$:

$$j_{ng} = 240 \times 10^{-6} \ p^2 \ [A/cm^2]$$

for Cu-Air low pressure normal glow. 10) Where, $p$ is gas pressure. The total surface area of
the electrode 10.7 cm in diameter is obtained to be 155 cm² (= 76 cm² plane area + 79 cm² rounded edge). Therefore, when the whole cathode surface is surrounded by normal glow, the value of the current is obtained to be 3.7 A, which is indicated as \( I_{\text{ng}} \) by arrow in Fig. 6. The glow voltage is almost constant in the case of current lower than 3.7 A while it increases with increasing current in a range higher than 3.7 A. This fact implies that the discharge changes from a normal glow to an abnormal glow at the discharge current of 3.7 A.

B. Current density

Figure 7 shows the relationship between discharge current at the time just prior to \( t_0 \) and circuit resistance \( R \) with gas pressure \( p \) as a parameter at electrode separation of 1.0 cm. The glow current decreases with the circuit resistance. The transient glow current can be regarded as being proportional to \( R^{-k} \) \((k<1)\) from the slope of the lines in log-log scale. Figure 8 shows the plotted cathode current density at the time just prior to \( t_0 \) in relation to circuit resistance \( R \) with gas pressure \( p \) at electrode separation of 1.0 cm. The broken lines represent the value calculated from the equation (2) for Cu-Air normal glow. The current density \( j \) is given by:

\[
  j = \frac{I_g}{S} \tag{3}
\]

where \( S \) is the cross-sectional area of the glow cylinder and obtained from the photograph of the negative glow on the cathode. In this work for \( R>60 \, \Omega \), the current density at 20 torr is almost independent of the circuit resistance and is close to the value derived from \( 240 \times 10^{-6} \, p^2 \). The current density, however, increases with the decrease of the resistance in a range of \( R<60 \ \Omega \). This fact indicates that a transient glow changes from the normal glow to the abnormal glow by making the resistance small. At 10 torr the current density of the glow discharge decreases with the resistance because the glow current decreases in a range of 1 to 200 \( \Omega \). The maximum value of the cathode current density of the glow discharge is 3.2 A/cm², which is almost two orders larger than the value obtained from the formula of Cu-air normal glow.

![Fig. 7 Dependence of transient glow discharge current on circuit resistance \( R \) at different values of gas pressure \( p \). d=1 cm.]

![Fig. 8 Current density on the cathode at the time just prior to \( t_0 \) as a function of circuit resistance \( R \) at different gas pressures. d=1 cm.]

C. Electron density

The value of \( E/p \), on the plateau of the \( V-I \) curve, in the positive column of the glow discharge was deduced from the measured values of the glow voltage. Figure 9 shows the plotted gap voltage just prior to \( t_s \) in relation to the electrode separation \( d \) with gas pressure \( p \) as a parameter. The circuit resistance is 1 \( \Omega \). The gap voltage decreases linearly with reducing electrode separation. The cathode fall voltage can be obtained to 285 V as “zero length voltage” \(^{11}\) by extrapolating the potential distribution across glow discharge to zero electrode separation. In the normal glow mode \((I < 3.7 \text{ A})\), the value of \( E/p \) is obtained to be 8.6 V/cm/torr and independent of the discharge current. At discharge current of 144 A (in abnormal glow mode), the \( E/p \) is 61.6 V/cm/torr. The electron density of the positive column \( N_e \) can be estimated using the following formula:

\[
N_e = \frac{j}{eW}
\]

where \( j \), \( e \) and \( W \) are current density, electron charge and electron drift velocity, respectively. The parameter \( W \) is calculated as a function of \( E/p \), \(^{12}\) and it is \( 4.5 \times 10^6 \text{ cm/s} \) for normal glow mode and \( 20.5 \times 10^6 \text{ cm/s} \) for abnormal glow at current of 144 A. The current density \( j \) in the abnormal glow mode can be determined by division of the total glow current by the cross section of the positive column; it was calculated to be 89.9 cm\(^2\). Therefore, the electron densities of the positive column can be estimated to \( 3.3 \times 10^{10} \text{ cm}^{-3} \) for normal glow \((I < 3.7 \text{ A})\) and \( 4.9 \times 10^{11} \text{ cm}^{-3} \) for abnormal glow \((I = 144 \text{ A})\).

Figure 10 shows the time variation of the electron density measured with Langmuir probe at the middle between the electrodes. In this experiment, the gas pressure and the electrodes separation were kept at 3 torr and 2 cm, respectively. In this condition, the glow-to-arc transition did not occur. The current when the normal glow plasma covered over the whole cathode was 0.33 A from calculation of equation (2). The peak current of the pulse glow discharge is almost 14 A, which is 40 times larger than the normal glow current 0.33 A. Therefore, the discharge belongs to the abnormal glow. The electron density rapidly increases to almost \( 3 \times 10^{11} \text{ cm}^{-3} \) after a formation of the
D. Energy dissipation for glow-to-arc transition

Figure 11 shows the energy dissipated in the gap during glow phase $E_g$ in relation to electrode separation at different gas pressures $p$ with circuit resistance of $1 \Omega$. The dissipated energy was obtained from the glow current and the breakdown voltage by solving the circuit equations (1) and

$$E_g = \int_0^t i(t) \cdot V_g(t) dt$$  \hspace{1cm} (5).

The values of dissipated energy $E_g$ are in a range from 0.1 to 0.7 J. Chalmers et al suggested that the criterion for a glow-to-arc transition is that a certain quantity of energy is dissipated in the gap during the glow phase.\(^\text{13}\) This suggestion is based on the fact that the dissipated energies obtained by Allen and Farish were approximately the same value, that is, 1.5 J.\(^\text{14,15}\) The present values from 0.1 to 0.7 J are much smaller than those values reported by Chalmers and larger than the values by Fujiwara et al.\(^\text{16,17}\) Therefore, the dissipated energy of the transient glow changes according to experimental condition and it cannot be used as criterion for a glow-to-arc transition. Moreover, the dissipated energy $E_g$ is regarded as generally increasing with electrode separation though the measured values are scattered.

The present visual observation shown in Figure 3 represents that the filamentary discharge is initiated near the cathode surface where the cathode fall occurs. The growth of the cathode attachment strongly suggests that the initiation of the discharge filamentation may be a result of the characteristics of the cathode fall region. Fujiwara et al suggested that the criterion for a glow-to-arc transition is that a certain quantity of energy is dissipated on the cathode during the glow phase.\(^\text{16}\) The dissipated energy on the cathode can be calculated if energy dissipated in the cathode fall region is obtained from the following equation:

$$E_C = V_c \int_0^t i(t) dt$$  \hspace{1cm} (6).

Fig. 11 Dependence of energy dissipated in the gap during glow phase $E_g$ on on electrode separation $d$ at different gas pressures. $d=1\text{ cm. } R=1\Omega.$  

Fig. 12 Dependence of energy dissipated in the cathode dark space during glow phase $E_C$ on electrode separation $d$ at different gas pressures. $R=1\Omega.$
In calculation of this equation, the measured value of zero length voltage 285 V was used as $V_c$. Figure 12 shows the plots of the energy dissipated in the cathode fall region during glow phase $E_c$ in relation to the electrode separation with different values of gas pressure $p$. These conditions are the same as those in Figure 11. Though the dissipated energy in the gap $E_g$ increased linearly with the electrode separation, the dissipated energy in the cathode fall $E_c$ is almost constant. This fact indicates that the increase of $E_g$ with electrode separation is caused by the increase of energy dissipation in the positive column whose length is nearly equal to the electrode separation. Moreover, Figure 12 reveals that the dissipated energy in the cathode fall $E_c$ has depends on gas pressure and decreases with increasing gas pressure.

Chang et al have reported that the thermal instability, which is a local perturbation of electron or gas density that enhances local joule heating, mainly caused the discharge filamentation.\(^7\) The dissipated energy density in the cathode fall region $H$ can be calculated using the following equation:

$$H = \frac{E_c}{S_c \cdot l_c}$$

(7)

where $S_c$ and $l_c$ are the cathode area (i.e. the cross-section of the glow discharge) and cathode dark thickness, respectively. In calculating this equation, a measured zero length voltage of 285 V was used for $V_c$ along with the data for $p l_c=0.23$ torr cm given a copper cathode in normal dc glow discharge. Figure 13 shows the plotted dissipated energy density $H$ in relation to the electrode separation with different values of gas pressure $p$. The conditions are same as those in Figure 11. The obtained values for dissipated energy density in the cathode fall region $H$ are almost constant in relation to the variable electrode separation and gas pressure and are equal to 0.035 J/cm\(^3\). In industrial applications the transient glow discharge runs under gas flow conditions. Gas replenishment will therefore have the effect of stabilization on glow discharges at atmospheric pressure.

**E. Production of glow discharge plasma using pulse modulator**

The pulse glow discharge without glow-to-arc transition can be produced using a pulse modulator. The typical waveforms of the glow discharge current and the applied voltage are shown in Fig. 14. The electrode separation and the gas pressure are 2 cm and 12 torr, respectively. The applied pulse duration was set to 35 $\mu$s at 1,000 pps (pulses per second) repetitive rate. Figure 14 shows 60-120 A glow discharge is generated with 600 V applied voltage. The glow discharge plasma is spatially uniform as shown in Fig. 15.
The gas temperature in the glow discharge plasma can be determined as rotating temperature of nitrogen molecule. Figure 16 shows the time-dependence of the rotating temperature in the pulse glow discharge plasma. The electrode separation and the gas pressure are 1 cm and 6 torr, respectively. The applied pulse duration was set to 10 μs at 1,000 pps repetitive rate. The rotating temperature of the nitrogen gas was obtained using spontaneous emission from the glow discharge $C^3Π_u - B^3Π_g$ emission bands of $N_2$. The temperature increases from 400 to 650 K during the glow discharge.

**IV. Conclusion**

With respect to the generation of high-density and large-volume plasma, the present research examined high-current transient glow discharge in dry air after static breakdown. A low inductance capacitor of $1.89\mu F$ and a discharge apparatus with co-axial configuration were used to produce a transient glow discharge with high current in excess of 150 A. Results showed that the high-current glow discharge with the 1 $\Omega$ circuit resistance has the cathode current density of 3.2 A/cm$^2$, which is almost two orders larger than the value obtained from the formula of Cu-air normal glow. The electron density in positive column of the high-current glow discharge were obtained to be $4.9\times10^{11}$ cm$^{-3}$ from calculation based on nitrogen swarm data. This value is close to the electron density $3\times10^{11}$ cm$^{-3}$ measured with Langmuir probe. The glow-to-arc transition starts and develops in the discharge region near the cathode. The dissipated energy density in the cathode fall region during the glow phase is almost constant against the gas pressure and the electrode separation having a value of 0.035
J·cm⁻³ under the present experiment’s conditions. The high-current glow discharge plasma was successfully produced with 35 μs duration at 1 kpps repetition rate using a pulse modulator.

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References
12 S. Takeda, Kitai Houden no Kiso (Tokyo Denki, Tokyo, 1990) 35. [in Japanese]