Dependence on the Operation Frequency of Negative Glow

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ABSTRACT
Measuring the Ne-Hg negative glow lamp (having no positive column), authors found the efficiency decreased as frequency increased. Authors measured the characteristics of this plasma to grasp the reason for it. There are two groups of electrons in this plasma. One group consists of first electrons whose peak energy at high frequency (HF) operation is higher than at low frequency (LF). The other consists of second electrons whose energy at HF operation is lower than at LF. There was the period without first electrons at HF operation. From these results, authors attribute the reason for the decreasing efficiency to the followings. (1) The period of the energy transfer from first electrons to second electron at HF operation is shorter than at LF, because there is the period without first electrons at HF operation. (2) Ionization loss at HF operation is higher than at LF, because of the higher peak energy of first electrons. Lastly authors checked the negative glow performance of 2 lamps, which were Ne-Hg lamp and Ar-Hg lamp with positive column, to compare with that of Ne-Hg lamp without positive column, and confirmed that there are no difference among the negative glow performance of these 3 lamps. It is considered from these measurement that the peak of cathode fall voltage at HF operation is higher than at LF, in spite of the cathode fall voltage is lower at HF in r.m.s.

KEYWORDS: negative glow, plasma characteristics, frequency, cathode fall voltage, spectrum

1. Introduction
Many researches concerning with the characteristics of the plasma in the vicinity of the cold cathode have been made\(^{(3)}\). Characteristics of negative glow in the fluorescent lamp, whose cathode is hot cathode, have been researched experimentally by Druyvesteyn\(^{(3)}\) and Waymouth\(^{(3)}\), and have been calculated by Ingold\(^{(3)}\) and Coe\(^{(3)}\). Watanabe\(^{(3)}\) and Misono\(^{(3)}\) recently researched the cathode fall voltage of the fluorescent lamp at high frequency operation. In the meantime, the characteristics of the negative glow lamp in DC operation have been experimentally researched by Matsuno et al\(^{(3)}\) and calculated by Uetsuki et al\(^{(3)}\). But the characteristics of the negative glow lamp at high frequency operation has not been reported extensively\(^{(3)}\).

The authors made a Ne-Hg negative glow lamp having no positive column, and measured the relation between efficiency and frequency. As the result they found out the efficiency decreased as the frequency increased. This is a different phenomenon from that observed in a regular fluorescent lamp. Authors made some experiments to understand this phenomenon.

The purposes of this paper are to clear the reason of this phenomenon and to understand the behavior of the cathode fall voltage at high frequency operation by measuring the characteristics of the plasma in the vicinity of the cathode. The structure of this paper is as follows. Section 2 is a description of the experiment results. In this section firstly the dependence of the efficiency of the Ne-Hg negative glow lamp on the operating frequency, secondly the dependence of the dynamic characteristics of the electric wave form of this lamp on the operating frequency, thirdly the dependence of the intensity of Ne-spectrum of this lamp on the operating frequency, and finally the dependence of the characteristics of the plasma on the operating frequency are described. Section 3 is a description on the results of the discussion of these experiments. In section 4, authors try to identify the difference in the characteristics of the negative glow lamp in the negative glow lamp and in the regular fluorescent lamp. In this section, the dependence of the characteristics of Ne-Hg negative glow on the operating frequency is described followed by the explanation that the dependence of the characteristics of Ar-Hg negative glow on the operating frequency is basically the same as that of Ne-Hg negative glow. Finally authors summarizes their conclusion in section 5.

2. Experiments
2.1 Efficiency vs. Frequency
Fig. 1 shows the lamp profile used for experiment. Outer diameter of this lamp is 70mm, and the distance between cathode and anode is 15mm. This lamp has Ne and Hg
whose pressure are 200Pa and 0.8Pa respectively. Hg pressure was controlled by the cold spot temperature of this lamp. Fig.2 shows the circuit used for experiment. Fig.2(a) and fig.2(b) are the AC circuit and the rectified AC circuit respectively. In these figure “Function generation” is HP-3314 (made by HEWLETT PACKARD) and "Amplifier" is NF-4015 (made by NF CORPORATION). The root means square (r.m.s) of lamp current was 1.5A.

Fig.3 shows the measurement results of the relationship between the efficiency of this lamp and the operating frequency. Concerning with ordinate, the efficiency of this lamp which was operated by DC is defined as 100. There was no difference between in AC operation and in rectified AC operation. The efficiency and the input power decreased as the frequency increased. This means the r.m.s. of the lamp voltage decreased, because the lamp current is constant.

As there was no difference between in AC operation and in rectified AC operation, phosphor was not coated in the lamp (Fig.4) for more convenient for the measurement using
a Langmuir probe. The lamp specification is basically the same as the lamp in Fig.1 except that one electrode is anode made by molybdenum. The operating circuit was shown in Fig.5, and the lamp was measured at 50Hz(low frequency) and at 50kHz(high frequency). The wave form of power source is sinusoidal. These are actually power source frequency, therefore the actual operating frequency is twice of them because of being rectified. But, in this paper, the operating frequency is defined as that of power source.

![Circuit for DC negative glow lamp](image)

**Fig. 5** Circuit for DC negative glow lamp

### 2.2 Dynamic characteristics of the electric wave form

Fig.6(a) and Fig.6(b) show the electric wave form of this lamp at 50Hz and 50 kHz respectively. In this measurement the lamp current is 2A, and the cathode was heated to 900°C auxiliarily. This condition is suitable for this cathode, because the life time of this lamp in DC operation was more than 10,000 hrs in this condition. From this measurement the following results were observed.

![Graph: Lamp current and voltage of negative glow lamp](image)

**Fig. 6** Lamp current and voltage of negative glow lamp

1. Fig.6(a) shows that there exists the period in which the discharge goes out at 50Hz.
2. Fig.6(b) shows that the discharge is continuous, and that there exists the distortion in the wave forms of the lamp current and voltage. The peak of the lamp current is delayed around 2 μs from that of the lamp voltage.

![Graph: Difference of the operation stage of negative glow lamp between 50Hz and 50kHz](image)

**Fig. 7** Difference of the operation stage of negative glow lamp between 50Hz and 50kHz

### 2.3 The spectrum vs. Frequency

Fig.7(a) and Fig.7(b) show the operation states at 50Hz and 50kHz respectively. Fig.8 shows those spectrum. Fig.9 shows the time dependence of the lamp voltage and the lamp current and Ne-spectrum (640.2nm) at 50kHz. The spectroscope and photo-multiplier used for this measurement are CT-25C (BUNKOH-KEIKI Co., Ltd) and R 446 (HAMAMATSU PHOTONICS K.K.) respectively. The operating conditions were that the r.m.s. of lamp current was 1.5A and the cathode was heated to 900°C auxiliarily. The operation states of this lamp is the same as that of the lamp shown in fig.2. From this measurement the
following results were observed.

1. Fig.7 and fig.8 show that Ne-spectrum cannot be observed at 50Hz but at 50kHz.

2. Fig.9 shows that Ne-spectrum is synchronized with the wave form of lamp current. It becomes stronger at the point the current gets distorted, and is strongest at the time the voltage of power source is strongest.

2.4 Plasma characteristics vs. frequency

The time dependence of the plasma characteristics, electron density and electron temperature, were measured by a Langmuir probe whose diameter and length are 0.1mm and 1.5mm respectively. The operating circuit and measurement system are shown in fig.10. The lamp specification is basically the same as that shown in fig.4. A Langmuir probe is positioned between the cathode and the anode, and 5mm far from the cathode. The operating conditions were that the r.m.s. of lamp current was 2A and the cathode was heated to 900ºC auxiliarily.

Fig.11 shows the probe performance in the relation between the electron current flowing into probe (I_e) and the potential difference from anode to probe (V_p) at 50Hz. This probe profile does not change during the period that the discharge occurs, therefore it does not depend on the time at 50Hz.

Fig.12 shows the probe characteristics of 50kHz. From this results, it can be seen that this probe profile depends on the time at 50kHz. Fig.12(a) and fig.12(b) show the probe characteristics when the voltage of power source (V_s) are peak and zero respectively.

Fig.13 and fig.14 show the time dependence of the measurement results at 50Hz and at 50kHz respectively. (a), (b) and (c) show the relation between the source voltage and the time, the time dependence of the electron density and that of the electron temperature respectively. From these data, the followings can be seen.

1. This profile of 50Hz shown in fig.11 does not depend on the time, and seems to be the the same as that of DC operation (10). This means there exist two groups of electrons, which are first electrons having non-Maxwellian distribution and second electrons having Maxwellian distribution, in this plasma (10). The electron density and
temperature mentioned above mean that of the second electrons.

Fig. 13 shows that, at 50Hz, the electron temperature is constant and the electron density changes in the period that the discharge occurs. And this electron temperature seems to be the same as that of DC operation\(^{11}\).

By comparing this probe performance with that of 50Hz, it can be seen that the peak energy of first electrons of 50kHz shown in fig.12(a) is higher than that of 50Hz\(^{11}\). By comparing fig.12(a) with fig.12(b), it can be seen that the electron temperature varies with time.

(3) Fig. 13 and fig. 14 show that the electron temperature of 50kHz is lower than that of 50Hz.

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**Fig. 12 Probe characteristics at 50kHz operation**

(2) Fig.12(a) shows there exist two groups of electrons as mentioned above when Vs is peak at 50kHz operation. Fig.12(b) shows there does not exist first electrons at the time that Vs is zero at 50kHz operation.

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**Fig. 13 Time dependence of plasma characteristics at 50Hz operation**
3. Discussion

3.1 Plasma characteristics vs. Frequency

Firstly authors consider about the cathode fall voltage. Uetsuki et al.\(^{1)}\) reported that the energy of first electrons is equal to the cathode fall voltage. Therefore the followings can be considered.

At low frequency operation (50Hz), as mentioned in 2.4(1), the cathode fall voltage does not depend on time, and is the same as in DC operation. This is because the ionization process in this plasma can follow the time variation of source voltage at low frequency, therefore the cathode fall voltage needs to vary with time for supplying the current which is demanded from circuit. This phenomenon can be explained from Schottky effect, which will be mentioned in section 3.2.

From these results, it can be considered that the peak value of the cathode fall voltage at high frequency operation is higher than at low frequency where the cathode fall voltage is constant.

Secondly authors observed the electron temperature of second electrons. As mentioned in 2.4(3), electron temperature of second electrons at high frequency (50kHz) is lower than at low frequency (50Hz). The reason of this phenomenon is considered to be the followings.

(1) There exists the period where the first electron cannot exist (see 2.4(2)) at high frequency. In the meantime, at low frequency, the first electron always exists in the period that the discharge occurs. The second electrons can get the energy only from first electrons through electron-electron collision. Therefore the second electron cannot get the energy all the time at high frequency, but can get it all the time at low frequency. As the result, the energy of second electrons (electron temperature) at high frequency operation is lower than at low frequency.

(2) There exists the period that the energy of first electrons at high frequency is higher than at low frequency. The cross section of electron-electron collision is inversely proportional to the fourth power of the relative velocity\(^{1)}\), therefore the ratio of energy transferred from first electrons to second electrons is lower in this period compared with the ratio at low frequency. As the result, the energy of second electrons (electron temperature) at high frequency operation is lower than at low frequency.

3.2 The spectrum vs. Frequency

As mentioned in 2.3(1), the discharge has stronger Ne-spectrum at high frequency than at low frequency. This result does not contradict the result mentioned in 2.4(2) that the maximum energy of first electrons at high frequency is bigger than at low frequency. This is because the higher energy is necessary to radiate Ne spectrum in Ne-Hg discharge.

To understand the phenomenon in the vicinity of cathode, the authors divided one cycle into 3 periods which shown as "A"area, "B"area, and "C"area in fig.9. The phenomena in these areas can be considered as follows.

In "A"area, the lamp current (\(I_a\)) can be supplied by the thermal electron current (\(I_{th}\)) emitted from the cathode, because \(I_{th} < I_{ne}\). This means the cathode fall voltage seems to be zero in "A"area. \(I_{th}\) is expressed by the following formula.

\[
I_{th} = S J_a = S a T^2 \exp(-b/T)
\]  \hspace{1cm} (1)

where \(S\) and \(T\) are the cathode surface area and the cathode temperature respectively. \(a\) is constant determined
by the cathode materials and \( b \) is also constant related to work function.

In "B" area and "C" area, \( I_n \) cannot be supplied only by \( I_m \), because \( I_n > I_m \). As the result, the cathode fall voltage must be formed in these areas. The cathode fall voltage increases in "B" area, and decreases in "C" area. This phenomenon is well known as Schottkey Effect. In these areas \( I_n \) is expressed by the following.

\[
I_n = I_0 \exp(0.40 E^{1/2} / T)
\]  

(2)

where \( E \) is the electric field in the cathode sheath which varies with time. The time variation of \( E \) is attributed to time variation of the cathode fall voltage. This contradicts neither the measurement result that Ne spectrum varies with time, nor the result mentioned in 2.4(2) that the maximum energy of first electrons at high frequency is bigger than at low frequency.

3.3 Dynamic characteristics of the electric wave form

As mentioned in 2.2, the phase distance between current and voltage cannot be observed at low frequency but can be observed at high frequency. The reason can be considered as the following.

As mentioned in 3.1, at low frequency, the ionization process in this plasma can follow the time variation of source voltage. Therefore, the current can follow the voltage. While, at high frequency, the ionization process in this plasma cannot follow the time variation of source voltage. Therefore, the cathode fall voltage needs to vary with time for supplying the current which is demanded from circuit. As the result, the phase distance between current and voltage can be observed at high frequency.

When the cathode fall voltage becomes maximum, the first electrons having maximum energy are emitted to the plasma. As the energy is considered to be the same as the cathode fall voltage, it should be 25 eV. The first electrons are disappearing on the way to the lamp wall[21]. Their density is zero at the wall in the lamp used for this measurement[11]. Provided the first electrons go to the lamp wall with constant velocity and with scattering isotropically, the time "\( t \)" in which they travel the distance "\( R \)" should be expressed as follows.

\[
t = R^2/(v \lambda)
\]

where \( v \) and \( \lambda \) are the velocity of the first electrons and mean free path respectively. In this case \( t=1.4 \mu s \), because \( R=35 \mu m \), \( v=3 \times 10^6 \) m/s and \( \lambda=0.3 \mu m \) [22]. This value (1.4 \( \mu s \)) is corresponding to the phase distance between current and voltage obtained by the measurement (fig.6(a) and fig.9). This means that the current increases while the first electrons exist.

3.4 The efficiency vs. frequency

As mentioned in 2.1, the efficiency of this negative glow lamp decreases as the operating frequency increases. The reason is considered as the followings.

(1) The energy of the second electrons becomes lower as the operating frequency increases.

It is not the first electrons but the second electrons that contribute to the radiation of Hg (253.7nm), because the density of the second electrons is higher than that of another. Therefore the decrease of energy of the second electrons results in the decrease of lumen efficiency.

(2) The energy of the first electrons becomes higher as the operating frequency increases.

The first electrons mainly cause the ionization and the radiation of Ne, because their energy is high. When their energy becomes higher, the ionization ratio increases. As the result, the efficiency decreases.

4. Negative glow lamp vs. negative glow in the fluorescent lamp

From a series of measurements mentioned above, authors could say that the peak of the cathode fall voltage at high frequency operation is higher than at low frequency operation. This measurement result was different from the result regarding the cathode fall voltage in the fluorescent lamp which had been reported by Watanabe[8]. To analyze this contradiction, authors checked whether there is any difference in the characteristics of negative glow between in the negative glow lamp and in the lamp having the positive column by comparing Ne-spectra in the vicinity of the cathode of these lamps. The lamp having the positive column is the same condition as the negative glow lamp regarding the measurement system and the enclosed gases (Ne 200Pa and Hg 0.8Pa). The length of this lamp is 130mm, and the r.m.s. of the lamp current is 0.6A.

Fig. 15 Circuit for Ne-Hg lamp having positive column

Fig.15 shows the operating circuit for this lamp. Fig.16 shows the dynamic characteristics of the wave forms of the lamp current, the lamp voltage and Ne-spectrum (640.2nm), where (a) and (b) are at 50Hz operation and at 50kHz operation respectively. These data show that the intensity of Ne-spectrum at 50kHz is much stronger than at 50Hz. This trend is the same as that of the lamp operated by rectified AC circuit. It can be considered from these results that there is no difference basically between the negative glow lamp and the negative glow in the lamp having positive column.
Lastly authors checked the dependence of Ar-spectrum intensity of the negative glow in the general fluorescent lamp on the operating frequency. The measurement results are shown in fig.17, where (a) and (b) are at 50Hz and at 50kHz respectively. It can be seen from these data that the intensity of Ar-spectrum increases and Hg-spectrum decreases as the frequency increases. This is consistent with the result mentioned above that the peak of the cathode fall voltage increases as the operating frequency increases in Ne-Hg discharge.

![Fig. 17 Difference of the spectrum of Ar-Hg lamp negative glow between 50Hz and 50kHz](image)

5. Conclusion

The characteristics of Ne-Hg negative glow lamp (having no positive column) was measured with different frequencies. The results showed that the efficiency decreased as frequency increased, which is opposite to the case of the fluorescent lamp. The plasma characteristics were measured by Langmuir probe and spectroscopy to analyze this phenomenon. As the result, it could be got that the peak of the cathode fall voltage increases as the operating frequency increases in this Ne-Hg negative glow lamp. This result was different from the result regarding the cathode fall voltage in the fluorescent lamp which had been reported by Watanabe\(^6\), therefore any difference in the characteristics of negative glow between in the negative glow lamp and in the lamp having the positive column was checked. The result was that there is no difference basically between in these two lamps. Lastly characteristics of negative glow, regarding Ne-Hg lamp and Ar-Hg lamp with positive column, was checked by observing spectra. These measurement results shows that there is no discrepancy to the conclusion that the peak value of cathode fall voltage at high frequency operation is higher than at low frequency.
Appendix (Operating circuit and measurement system for plasma characteristics)

Fig. 10 shows the operating circuit and measurement system for plasma characteristics which varies with time. This system is considered to reduce the total measurement time compared with the usual measurement system like a so-called box-car integrator, and consists of 5 parts which are the lamp operating circuit, the circuit supplying the voltage to Langmuir probe, the trigger circuit, the digital oscilloscope, and the computer. This system works like as follows.

Appendix Fig. 1 Trigger circuit of Probe measurement system

Appendix Fig. 2 Time chart of signal in trigger circuit

After the lamp is operated at some condition, the voltage, whose potential is lower than the anode, is applied to Langmuir probe. The trigger circuit detects that moment, and calculates the timing of trigger output by checking the phase of the operating waveform. The digital oscilloscope starts measuring the probe potential and current when it detects the output of the trigger circuit. These data measured by the digital oscilloscope are saved to the computer.

Appendix Fig. 3 shows the circuit diagram of the trigger circuit.

Reference

(3) Druyvesteyn, M.J. : "Der Niedervoltvogen", Zeit Phys. 64, pp.781-798 (1930)