Surface-charge measurements in microgap dielectric barrier discharge using bismuth silicon oxide crystals

S Mukaigawa\textsuperscript{1,2}, H Matsuda\textsuperscript{1}, H Fue\textsuperscript{1}, R Takahashi\textsuperscript{1}, K Takaki\textsuperscript{1,2}, T Fujiwara\textsuperscript{1,2}

\textsuperscript{1}Faculty of Engineering, Iwate University, Morioka 020-8551, Japan
\textsuperscript{2}Soft-Path Engineering Research Center (SPERC), Faculty of Engineering, Iwate University, Morioka 020-8551, Japan
e-mail: mukaigaw@iwate-u.ac.jp

Abstract. A surface-charge measurement system based on the Pockels effect in bismuth silicon oxide dielectric crystals was constructed for measuring the surface-charge density of the dielectrics in the microgap dielectric barrier discharge. We re-examined the calculation methods of the surface-charge density from the voltage applied to the BSO crystal, obtained by laser interferometry. The charge calculated using the circuit equation coincided with the that obtained using the discharge current. Under certain experimental conditions, the maximum values of the surface charge density in the discharge cell with and without a protection glass were +2.0 and +2.5 nC/cm\textsuperscript{2}, respectively.

1. Introduction
Dielectric barrier discharge is used in many fields such as plasma surface treatment, lighting, and plasma display panels, and is often used in the production of microplasma. The charging effect of the inner wall in microplasma is more important than that in macroscale discharge. The charge accumulated on the dielectric surface is an important parameter controlling the minimum value of the sustaining voltage and its uniformity [1-3]. Because the surface dielectric barrier charges accumulated in the half-cycle of the driving voltage favor the reappearance of the discharge, surface charges play a key role in the generation and stabilization of emerging patterns. Thus, it is essential to measure the quantity and distribution of surface charges in self-organized discharge [4-6].

Recently, the measurement of surface charge in bismuth silicon oxide Bi\textsubscript{12}SiO\textsubscript{20} (BSO) crystals using the Pockels effect has become one of the most important methods for understanding the generation of self-organized plasma discharge and plasma photonic crystal applications [7-16]. When performing charge measurements by the laser interference method using the Pockels effect in BSO, the directly observable physical quantity is the intensity of laser light, and the physical quantity deduced from this intensity is the voltage applied to a BSO crystal. When deducing the electric charge accumulated in a BSO crystal surface from this voltage, some researchers tacitly assume that $Q = CU_{BSO}$, where $Q$ is the charge accumulated on the BSO crystal, $C$ is the capacitance of the BSO crystal, and $U_{BSO}$ is the voltage applied to the BSO crystal induced by the applied electric field and others employed the inverse calculation from the potential distribution to the charge distribution on the dielectric surface [17, 18].

In this study, we re-examined the simplified calculation method of the surface-charge density from the voltage applied to the BSO crystal obtained by laser interferometry. In the surface-charge
measurements of these electro–optic crystals, the crystal acts as the dielectric barrier. In the present study, we also introduced a glass layer on the surface of the BSO crystal to prevent damage from plasma irradiation and investigated the influence of the glass layer on the measured surface charge.

2. Basic principles and experimental setup

The refractive indices of electro-optic materials such as single-crystal BSO change when an electric field is applied. Birefringence causes the refractive index to differ at orthogonal directions in a crystal. When an electric field is applied to BSO, the phase retardation \( \Delta \phi \) between the ordinary and extraordinary rays is given by

\[
\Delta \phi = \frac{2\pi}{\lambda} n_0^3 r_{41} U_{BSO},
\]

where \( \lambda \) is the wavelength of light, \( n_0 \) is the normal refractive index, and \( r_{41} \) is the coefficient of the Pockels effect.

Figure 1 shows the schematic of the optical measurement system. It consists of a He-Ne laser with a wavelength of 632.8 nm, an analyzer, a quarter-wave plate, a polarizer, a band pass filter, a semiconductor detector (Hamamatsu Photonics C6386-01), and a discharge cell. When the incident light passes through the polarizer, the light becomes linearly polarized as only the +45°orientation can pass through it. Subsequently, after the quarter-wave plate, it changes to circularly polarized light. When electric field is applied to the BSO crystal, light phase retardation appears and the light changes from circularly polarized to elliptically polarized. Therefore, light intensity changes after it passes through the analyzer at -45° orientation. The output light intensity \( I \) is given by the following equation:

\[
I = \frac{I_0}{2} \left( 1 + \sin \left( \frac{2\pi}{\lambda} n_0^3 r_{41} U_{BSO} \right) \right),
\]

where \( I_0 \) is the intensity of the linearly polarized light. According to Eq. (2), the voltage applied to the BSO crystal, \( U_{BSO} \), can be derived from the light intensity. When the phase retardation \( \Delta \phi \) is small, the light intensity \( I \) is approximated by the following equation:

\[
I = \frac{I_0}{2} \left( 1 + \frac{2\pi}{\lambda} n_0^3 r_{41} U_{BSO} \right).
\]

Figure 1. Experimental apparatus.  
Figure 2. Structure of the microgap discharge cell.

Figure 2 shows the structure of the microgap discharge cell. It consists of a dielectric layer (glass), a pair of spacers (glass), and the BSO crystal. The thickness of the BSO crystal \( a_{BSO} \) was 300 µm, the
relative permittivity $\varepsilon_{\text{BSO}}$ was 56, the normal refractive index $n_0$ was 2.56, and the coefficient of Pockels effect $r_{41}$ was 5 pm/V. Influence of optical rotation in BSO is negligible because of the thickness of the BSO sample [19]. An antireflective coating for light of 632.8 nm wavelength was applied to the BSO crystal surface. In case (a) that the BSO crystal was not protected from the discharge by the glass layer, a 450-µm-thick glass plate was used for the upper and lower dielectric layers. In case (b) that the BSO crystal was protected from the discharge by a glass layer, a 300-µm-thick glass plate was placed between the spacers and the BSO crystal, and 450-µm- and 140-µm-thick glass plates were used for the upper and lower dielectric layers, respectively. This was done to equalize the voltage applied to the BSO crystal by making the resultant capacity of the discharge cell almost the same. The relative permittivity of the glass plates was 7. The discharge gap length was controlled by the thickness of the spacer, which was 140 µm long. Indium Tin Oxide (ITO: resistivity $10^{-20} \Omega/\text{cm}^2$, area 10×15 mm$^2$) was deposited as an electrode on the surface of the dielectric. The ITO coated one side of the dielectrics. We applied a sinusoidal voltage with 100 kHz frequency and 1000 V amplitude to the upper ITO electrode. The lower ITO was grounded. The discharge was generated between the gaps. We introduced helium gas into the gap with a flow velocity of 14.0 m/s. The applied voltage and current were measured using a high voltage probe (Tektronix P6015A) and Rogowski coil (Pearson CT2877). The discharge current was calculated from the measured current.

3. Calculation of surface charge

When applying the experimental optical system to measure the surface charge, it is necessary to accurately evaluate the relation between the surface charge density and voltage applied to BSO($U_{\text{BSO}}$). The simplest calculation method assumes that all the electric lines of force of the electric charge accumulated on the BSO crystal surface pass through the BSO crystal. The relation between the surface-charge density $\sigma$ obtained by this method and voltage $U_{\text{BSO}}$ is expressed as follows:

$$U_{\text{BSO}} = U_{\text{BSO}}^{\text{ex}} + \frac{\sigma}{C_{\text{BSO}}},$$

where $C_{\text{BSO}}$ is the capacitance of the BSO crystal per unit area, which is expressed as $C_{\text{BSO}} = \varepsilon_0 \varepsilon_{\text{BSO}} / a_{\text{BSO}}$; $\varepsilon_0$ is the vacuum permittivity; and $U_{\text{BSO}}^{\text{ex}}$ is the voltage of the BSO crystal induced by the external electric field. Since the voltage component due to the surface charge and the voltage component due to the external electric field are contained in $U_{\text{BSO}}$, in order to measure the surface charge by laser interferometry, the effect of the voltage due to the external electric field on the laser light intensity $I$ must be removed. Subsequently, the laser light intensity $I_r$ measured in the absence of surface charge (reference light) is subtracted from the intensity of the laser light $I$ measured when the BSO crystal is charged. $I_r$ is expressed as follows:

$$I_r = I_0 \left(1 + \frac{2\pi}{\lambda} n_0^4 r_{41} U_{\text{BSO}}^{\text{ex}}\right),$$

where $U_{\text{BSO}}^{\text{ex}}$ is the voltage applied to the BSO crystal without surface charge. Assuming $U_{\text{BSO}}^{\text{ex}} = U_{\text{BSO}}^{\text{ex}}$ and using Eqs. (3) and (5), the following equation is obtained:
The method for determining the relation between the surface-charge density and voltage $U_{BSO}$ applied to the BSO crystal using a circuit equation is an alternative method. The equivalent circuit of the discharge cell in figure 2 is shown in figure 3. The circuit equation is expressed in terms of the surface-charge density $\sigma$, obtained by this method and the voltage $e$ applied to the electrodes, as follows:

$$\left\{ \begin{array}{l}
e = U_{BSO} + 2U_b + U_g \\
Q - Q_g = \sigma_t \\
Q = C_b U_b = C_{BSO} U_{BSO} \\
Q_g = C_g U_g
\end{array} \right. , \tag{7}$$

where $C_b$ is the capacitance of the dielectrics per unit area, $C_g$ is the capacitance of the discharge gap per unit area, $U_b$ is the voltage applied to the dielectrics, $U_g$ is the voltage applied to the discharge gap, $Q$ is the charge density in the dielectrics and BSO crystal, and $Q_g$ is the charge density accumulated in the discharge gap (the difference between $Q$ and $\sigma_t$). The following equation is obtained from Eq. (7):

$$U_{BSO} = \frac{C_b}{C_{BSO}} \left( e + \frac{\sigma_t}{C_g} \right) , \tag{8}$$

where $C_T$ is the series capacitance of $C_{BSO} \cdot C_b$, and the two $C_g$, and is expressed as $1/C_T = 1/C_{BSO} + 1/C_b + 2/C_g$. The first term in Eq. (8) is equal to the voltage of the BSO crystal calculated by the capacitive voltage division in series capacitors. Although $U_{BSO} = U_{BSO}$ had to be assumed in the first method, it is automatically filled in the present method. The second term in Eq. (8) differs from that in Eq. (6) $C_g/C_T$ times because the electric lines of force emitted by the surface charge are divided into the BSO crystal and discharge gap side. Using Eqs. (3), (5), and (8), the following equation is obtained:

$$\sigma_t = (I - I_r) \frac{2}{I_0} \frac{C_{BSO}}{2\pi n_0^3 r_{a1} / \lambda} \cdot \frac{C_g}{C_T} . \tag{9}$$

The charge density $\sigma_t$ differs $C_g/C_T$ times from the surface charge density $\sigma$ calculated by the first method. The value of $C_g/C_T$ is 1.85 with the structure of figure 2(a), and is 2.12 with the structure of figure 2(b).

4. Results

Figure 4 shows the applied voltage and discharge current waveform in the discharge cell without the protection glass. The discharge current was calculated following Liu et.al. [20]. We define the starting time ($t=0$) as the time at which the driving voltage is 0 V. Double peak current occurs per half period of the driving voltage. The first peak appears at $t = 0.4 \mu s$, and the second appears at $t = 1.6 \mu s$. The discharge current reaches the maximum value of 20.8 mA at 0.4 $\mu s$. The time width at which the current waveform reaches more than 20% of the maximum value is 0.3 ns. A glow discharge covers the entire discharge area when the current pulse appears.
The time variations in the laser light \( I \) and reference light \( I_r \), are shown in figure 5 with the applied voltage waveform. When we observed the reference light \( I_r \) at the applied voltage of 1000V, air was used to prevent the formation of discharge in the microgap. There is an obvious difference in the waveform \( I \) and \( I_r \), resulting from the surface charge on the BSO crystal.

![Figure 4](image4.png) **Figure 4.** Applied Voltage and discharge current waveform in case of glow DBD in atmospheric pressure helium; amplitude \( V_p=1000 \) V, frequency \( f=100 \) kHz.

![Figure 5](image5.png) **Figure 5.** Intensity of the output laser light \( I \) and reference light \( I_r \).

The time variation in the difference in the laser light and reference light, \( I-I_r \), in the half period of the positive voltage is shown in figure 6 with the discharge current waveform. The value of \( I-I_r \) is negative from \( t=0 \) to 2.1\( \mu \)s. The value of \( I-I_r \) begins to increase at \( t=0.4 \) \( \mu \)s when the discharge current starts to flow, and reaches the maximum thereafter. Similarly, the \( I-I_r \) synchronized with the discharge current at the half period of the negative voltage (\( t=5-10 \) \( \mu \)s). The change in the value of \( I-I_r \) and the movement synchronization of the charge due to the discharge current imply that the information on the amount of electric charges on the dielectric surface is included in \( I-I_r \).

Figure 7 shows the calculated surface-charge density and the discharge current waveform. Three methods were used to calculate the surface-charge density. That is, the charge was calculated using Eqs. (6), and (9), and the time integration of the discharge current. The BSO crystal surface was negatively charged before the electric discharge starts at \( t=0.4 \) \( \mu \)s. During this period, the values of the surface-charge density calculated by Eq. (6), Eq. (9), and the integration of the discharge current were -0.8 nC/cm\(^2\), -1.4 nC/cm\(^2\) and -2.4 nC/cm\(^2\), respectively. At the time \( t=0.4 \) \( \mu \)s of the first discharge, the charge density increased simultaneously and the discharge stopped at \( t=0.7 \) \( \mu \)s. The charge density did not change during \( t=0.7-1.7 \) \( \mu \)s. The values of the surface-charge density calculated by Eq. (6), Eq. (9), and the integration of the discharge current were +1.0 nC/cm\(^2\), +1.9 nC/cm\(^2\), and +0.5 nC/cm\(^2\), respectively. When the second discharge started at \( t=1.7 \) \( \mu \)s, the charge density increased again and reached a maximum. The values of the surface-charge densities calculated using Eq. (6), Eq. (9), and the integration of the discharge current were +1.4 nC/cm\(^2\), +2.5 nC/cm\(^2\) and +2.5 nC/cm\(^2\), respectively. Then, the charge density did not change till \( t=5 \) \( \mu \)s, and the BSO crystal surface was positively charged. In the half period of the negative voltage (\( t=5-10 \) \( \mu \)s), the charge density changed by synchronizing with the discharge current. The minimum values of the surface-charge density calculated using Eq. (6), Eq. (9), and the integration of discharge current were -0.8 nC/cm\(^2\), -1.5 nC/cm\(^2\), and -2.6 nC/cm\(^2\), respectively. Then, charge density did not change until \( t=10 \) \( \mu \)s, and the BSO crystal surface was negatively charged. A comparison of the calculation methods of the surface charge density shows that the calculation of the surface charge using the discharge current coincides with that using Eq. (9), whereas the calculation results based on Eq. (6) differ from those of the other two methods. Despite the simple assumption that all the electric lines of force of the electric charge...
accumulated on the BSO crystal surface pass through the BSO crystal, the calculation based on this assumption is not a good approximation.

Figure 6. Difference between laser light and reference light $I - I_r$.

Figure 7. Comparison of the surface-charge density calculated with Eq. (6) ($\sigma$), Eq. (9) ($\sigma_I$), and by integrating the discharge current $I_d$ ($\sigma_d$).

Figure 8 shows the time variation in the surface-charge density in the discharge cell with and without protection of the BSO crystal. The calculation based on Eq. (9) was used to evaluate the surface charge. When the discharge cell with protection glass was used, the large noise components were contained in the output voltage of the semiconductor detector. It is expected that a malfunction of the antireflective coating on the BSO surface due to the direct junction between the BSO crystal and cover glass causes multiple reflections. The maximum values of the surface-charge density in the discharge cell with and without the protection glass were +2.0 nC/cm$^2$ and +2.5 nC/cm$^2$, respectively. Despite equalizing the parameters of the equivalent circuit of the electric discharge cell, there was a difference in the surface density of the charge. The reason of this difference is that the state of the plasma changed because of the differences in the structure of the plasma/solid interface (e.g. secondary electron emission coefficient) [21].

5. Conclusion

The calculation method of the surface-charge density using laser interferometry and a BSO crystal was re-examined. It was observed that the signal $I - I_r$ synchronizes with the discharge current. Thus, the change in signal $I - I_r$ corresponds to the movement of the surface charge to the opposite side of the dielectric surface in the discharge region. Information regarding the surface-charge density was extracted by subtracting the signal of the reference light $I_r$ from the output light intensity $I$. Comparing the calculation methods of the surface-charge density, the calculation results of the surface charge using the discharge current coincide with those based on the circuit equation; however, the calculation results based on the assumption that all the electric lines of force of the electric charge accumulated on the dielectrics surface pass through the BSO crystal differ from those based on the other two methods. Furthermore, the surface-charge measurements using the BSO crystal were applied to a BSO crystal.
that was protected from discharge by a glass layer. When the applied voltage was 1000V and the flow velocity was 14.0 m/s, the maximum values of the surface-charge density in the discharge cell with and without the protection glass were +2.0 nC/cm² and +2.5 nC/cm², respectively.

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