Characteristics of Fluorine Negative Ions in Helicon-Wave Excited High-Density Carbon-Tetrafluoride Plasmas

URA Kenichiro, SASAKI Koichi and KADOTA Kiyoshi
Department of Electronics, Nagoya University, Nagoya 464-01, Japan

(Received 27 June 1996)

Abstract
Negative ion behavior in helicon-wave excited high-density carbon-tetrafluoride (CF₄) plasmas was examined with a time-of-flight mass spectrometer. As a result of mass spectrum measurements, only fluorine negative ions (F⁻) were observed in afterglow plasmas as the negative ion species. The F⁻ density increased immediately after the termination of the rf power into the plasma. During this period, the electron density decreased rapidly with a decay time constant of less than 20 μs. The experimental results of the relation between the F⁻ and electron densities showed several inconsistencies with the assumption that F⁻ was mainly produced by dissociative electron attachment to CF₄. In the present study, dissociative electron attachment to CF₃ radicals is proposed as a production process of F⁻ in low-temperature afterglow plasmas. In addition, pulse modulation of the rf power was tried to enhance the production of F⁻. Negative ions were obtained in each afterglow phase in the pulse-modulated plasma, resulting in the increase of the sum total of F⁻ during the entire discharge duration.

Keywords: fluorine negative ion, high-density carbon-tetrafluoride plasma, afterglow plasma, time-of-flight mass spectrometer, dissociative electron attachment, neutral radicals, helicon wave discharge, plasma etching

1. Introduction
In the fabrication of ultralarge-scale integrated circuits (ULSI), weakly ionized low-temperature plasmas employing halogen-containing gases are widely used for dry etching of materials. Recent ULSI fabrication demands precise patterning below quarter-micron with a high anisotropy, a high selectivity, and a high etching rate. In order to obtain the high anisotropy, an rf (600 kHz-10 MHz) power is usually supplied to the substrate holder, so that it is negatively self-biased with respect to the plasma and positive ions are accelerated to the substrate by the electric field in the ion sheath. The normal direction of the positive ion trajectory to the substrate surface results in the highly anisotropic etching. However, in polycrystalline silicon (Si) etching using high-density Cl₂ plasmas, there is a common problem of pattern distortion of a wedge-shaped sidewall etching ("notch") [1,2], which is considered to be attributed to that electrons are trapped on the sidewall and the positive ions charge up the bottom of the high-aspect-ratio pattern. The positive charges on the bottom of the pattern induce the bend of the ion trajectory. In addition, the accumulation of the positive charges on the gate electrode causes dielectric breakdown of the thin gate oxide film.

Recently, the importance of negative ions is strongly pointed out from the point of view of avoiding the sidewall notch and the breakdown of the gate oxide [3,4]. In the presence of negative ions, the sheath voltage between the plasma and substrate is reduced considerably. The positive charge on the bottom of the pattern can be neutralized by the negative ions during positive phases of the low-frequency (< 1 MHz) rf bias. The high etching rate is also expected in the presence of negative ions since etching reactions assisted by the negative ions are expected during positive phases of the rf bias. On the other hand, negative ions also play an important role in carbon-tetrafluoride (CF₄) plasmas...
Fluorine negative ions in high-density CF₄ plasmas

which are extensively used for selective etching of silicon dioxide (SiO₂) over Si. The large amount of negative ions have direct influence on the reaction kinetics and the transport of particles in plasmas. In addition, there is a possibility that fluorine negative ions (F⁻) etch SiO₂ selectively with a high etching rate due to the deoxidization property of F⁻ [5]. Accordingly, investigation about the production and loss processes of negative ions in low-temperature reactive plasmas is of particular importance to establish etching technology required for ULSI fabrication in next generation.

Characteristics of fluorine negative ions were studied by several authors in parallel-plate rf plasma sources with relatively high CF₄ gas pressures and low plasma densities [6,7]. An elaborate work by Kono et al. have shown that a major production process of F⁻ is electron attachment to CF₄, and major loss processes are recombination with CF₃ and associative detachment by CF₃ [8]. However, parallel-plate rf plasmas have limitation for the high etching anisotropy since the trajectories of positive ions are distorted by collisions with neutral molecules during passing through the ion sheath. Various types of high-density plasma sources operated under low gas pressures, such as electron cyclotron resonance (ECR) plasmas, inductively coupled plasmas (ICP), and helicon-wave excited plasmas, have recently been developed to realize anisotropic etching of the high-aspect-ratio pattern. Among these low-pressure plasma sources, helicon-wave excited plasmas can produce the highest electron density up to 10¹³ cm⁻³ under a low pressure of several millitorr [9]. In such very high-density plasmas, the reaction kinetics of F⁻ may be different considerably from those in the well-investigated high-pressure CF₄ plasmas.

This paper describes characteristics of negative ions in high-density CF₄ plasmas excited by helicon-wave discharges. A time-of-flight mass spectrometer was adopted for the measurements of the species and temporal variation of negative ions. In reference to the experimental results that the efficient productions of F⁻ were obtained in low-temperature afterglow plasmas, dissociative electron attachment to CF₃ radicals has been proposed as the dominant production process of F⁻, which is a different process from that in parallel-plate rf discharges. In addition, the pulse modulation of the rf power applied to plasmas was examined. The pulse modulation was tried by a pioneer work for the efficient production of metastable atoms in rare gas plasmas [10]. Recently, this technique was adopted in etching plasmas to improve various etching characteristics [11-13]. One reason for the improved etching is believed to be the efficient production of negative ions in the afterglow phases in the pulse-modulated plasmas. In the present study, the optimum modulation frequency for the most efficient F⁻ production was determined experimentally.

2. Experimental apparatus

2.1. Helicon-wave excited plasma source

A schematic of the experimental apparatus is shown in Fig. 1. A linear machine with a uniform magnetic field of 1 kG along the cylindrical axis was used. An rf power at a frequency of 13.56 MHz was applied to an m = 1 helical antenna [9] wound around a quartz glass tube of 3 cm in diameter and 25 cm in length. Pure CF₄ gas with a pressure range of 1.7-10 mTorr was adopted for discharges with a fixed gas flow rate of 10 cc (10 cc per minute at 1 atm and 25°C). The vacuum chamber was evacuated by a turbomolecular pump to an ultimate pressure of 3 × 10⁻⁶ Torr before feeding the CF₄ gas. The range of the rf power was up to 1.2 kW in the present experiment. The vacuum chamber was composed of a Pyrex glass tube (9 cm in diameter and 33 cm in length) and two stainless-steel
observation chambers \((20 \times 20 \times 10 \text{ cm})\). A grounded end plate with a hole of 3 mm in diameter was attached on the observation chamber of the down stream side, which was located approximately 55 cm away from the end of the helical antenna. A microwave interferometer was installed for the measurements of the electron density. The transmission chord of the probing microwave was located 20 cm away from the end plate. Plasmas were produced periodically with a repetition rate of 5 Hz and a discharge duration of typically 10 ms. In the pulse-modulated operation, the rf power during the discharge duration (10 ms) was amplitude-modulated by a square wave with a frequency of 1-20 kHz. The modulation depth was 100%. In the following, plasmas produced by the amplitude-modulated rf power with the 1-20 kHz square wave are denoted by “pulse-modulated plasmas”, while “continuously discharged plasmas” stands for the case that no modulations are adopted for the rf power during the 10 ms discharge duration.

2.2 Time-of-flight mass spectrometer

The time-of-flight mass spectrometer used for the negative ion diagnostics was attached behind the end plate. The detail of the time-of-flight mass spectrometer is schematically shown in Fig. 2 together with the potential distribution applied to the several electrodes. The arrangement of the electrodes has been modified from previous one [14,15] in order to improve the time resolution (spectral resolution of mass). Negative ions in plasmas were extracted along the cylindrical axis through a pinhole of 0.5 mm in diameter bored at the center of a positively-biased \((+70 \text{ V with respect to the ground potential})\) extraction electrode. The negative ion current increased with the positive bias voltage and was nearly saturated at approximately 70 V. Since the hole of the end plate was much smaller than the plasma column (3 cm in diameter), the plasma potential \((-15 \text{ V})\) was essentially determined by the grounded end plate. Hence, the potential of the extraction electrode was higher than the plasma potential, and negative ions can be extracted from both the discharge (during rf-on phase) and afterglow (during rf-off phase) plasmas. The extracted negative ions were accelerated by an acceleration electrode \((+2.5 \text{ kV})\) to avoid the divergence of the beam due to the space charge effect. After that, the negative ion beam was collimated by a focusing electrode \((+40 \text{ V})\) and was finally accelerated to an energy of 1.8 keV by a beam acceleration electrode. Between the acceleration and focusing electrodes, a gate electrode was used to obtain the ion mass spectrum with a high resolution. The potential of the gate electrode (usually grounded) was increased to 80 V suddenly by a pulse generator at a time when the mass spectrum measurement was carried out. The width of the gate pulse was typically 400 ns, which was short enough to separate ion species in the CF₄ plasma. The direction of the accelerated negative ion beam was controlled by the two pairs of deflector electrodes. After the 120 cm flight in free space, the negative ions were detected by a Faraday cup ion collector (25 mm in diameter). Secondary electrons appeared in the ion collector were
suppressed by applying a bias voltage of $-9$ V to the shielding electrode. The flight tube and the ion collector were floated at the potential of the beam acceleration electrode. Inside of the flight tube was differentially evacuated by a turbomolecular pump under $8 \times 10^{-5}$ Torr to obtain collisionless condition. Electrons extracted from the plasma together with the negative ions disappeared in the flight tube due to the divergent magnetic lines of force.

### 3. Experimental results

#### 3.1. Continuously discharged plasmas

A typical mass spectrum of negative ions is shown in Fig. 3, where the rf power and CF$_4$ gas pressure were 1 kW and 2.5 mTorr, respectively. The electron density in the discharge plasma was $2 \times 10^{12}$ cm$^{-3}$. The origin of the horizontal axis corresponds to the triggered time of the gate electrode, and was 20 $\mu$s after the termination of the rf power. The flight time of 9 $\mu$s shown in Fig. 3 coincides well with $L/(2m_eV)$ with the mass number $A = 19$, where $L$ is the flight length (1.2 m), $V$ is the beam acceleration voltage (1.8 kV), and $m_e$ and $e$ denote the mass of proton and the charge of electron, respectively. Hence the detected negative ion was identified as F$^-$. Other negative ions such as CF$_3$ observed in parallel-plate high-pressure discharges were not detected within the sensitivity of the present experiment. In addition, F$^-$ was observed only in afterglow plasmas. In discharge plasmas during the rf-on phase, no negative ions were detected. Therefore, when the time-of-flight mass spectrometer is used with the gate electrode always opened, the detected negative ion current roughly represents the temporal variation of relative F$^-$ density in the plasma.

Figure 4 shows the temporal variation of the negative ion density together with the electron density measured by the microwave interferometer for an rf power of 1 kW and a CF$_4$ pressure of 2.5 mTorr. The rf power to the plasma was turned off at 10.00 ms. The delay time in the negative ion density corresponding to the flight time was corrected in Fig. 4. As is seen from the figure, the F$^-$ density increased immediately after the termination of the rf power, and had a peak at 10.03 ms. The decay time constant of the electron density was very short. The electron density initially

![Fig. 3](image-url)

**Fig. 3** An example of the mass spectrum of negative ions for an rf power of 1 kW and a CF$_4$ gas pressure of 2.5 mTorr. The gate electrode was triggered at 20 $\mu$s after the termination of the rf power.

![Fig. 4](image-url)

**Fig. 4** Temporal variations of the F$^-$ and electron densities. The rf power was turned off at 10 ms.

![Fig. 5](image-url)

**Fig. 5** The F$^-$ density appeared in the afterglow is plotted as a function of the electron density in the discharge plasma. The electron density was controlled by two ways: by changing the rf power with the gas pressure being fixed at 2.5 mTorr (solid squares) and by changing the gas pressure with the rf power being fixed at 1 kW (solid circles).
decreased with a time constant of 32 μs during 10.00-10.02 ms. After that, the decay time constant of the electron density became as fast as 13 μs. For all the discharge conditions, the decay time constant of the electron density after 10.02 ms was shorter than 20 μs. This rapid decay time constant is one order shorter than the ambipolar diffusion time of the usual system consisting of electrons and positive ions.

The measurements of the F⁻ and electron densities were repeated for various rf powers and CF₄ gas pressures. Figure 5 shows the relation between the peak F⁻ density in the afterglow plasma and the electron density in the discharge plasma. The electron density was controlled in two ways: by changing the rf power with a fixed gas pressure of 2.5 mTorr, and by changing the gas pressure with a fixed rf power of 1 kW. In the present helicon-wave excited plasma source, the higher electron density was obtained for the higher rf power and the lower gas pressure. The rf power and gas pressure in each data point are indicated in the figure. It is clear from the figure that, for the same electron density, the higher F⁻ density was obtained for the lower CF₄ gas pressure.

The relation between the F⁻ and electron densities is also plotted in Fig. 6. In this case, the electron density in the discharge plasma was varied by shortening the discharge duration from 10 ms with the rf power and CF₄ gas pressure being fixed at 1 kW and 2.5 mTorr, respectively. Four data points shown by open circles were obtained by 10 ms discharges for various rf powers of 0.7-1 kW. For the same rf power and CF₄ gas pressure, the F⁻ density was not determined by the electron density uniquely. The F⁻ density was strongly dependent on the discharge duration, and a very small F⁻ density was obtained for a discharge duration of 0.2 ms.

3.2. Pulse-modulated plasmas

As has been described, in the present helicon-wave excited plasmas, fluorine negative ions were generated only in the afterglow. Hence, when the rf power applied to the plasma is pulse-modulated by a square wave, the generation of F⁻ is expected in each afterglow phase periodically. Figure 7 shows the temporal variations of the F⁻ and electron densities during the entire discharge duration when the CF₄ gas pressure and the instantaneous rf power were 2.5 mTorr and 1 kW, respectively. The frequency and duty factor of the square wave used for the modulation were 10 kHz and 50%, respectively. Although detailed depiction is not clear in the figure, F⁻ appeared in each afterglow phase when the rf power was terminated. The peak electron density in the rf-on phase increased initially and had a steady-state value of $1 \times 10^{12}$ cm⁻³ after 2 ms, which was approximately 60% of the electron density of the continuously discharged plasma for the same rf power and gas pressure. In contrast with the electron density, the F⁻ density increased gradually after 2 ms. When the discharge duration was extended longer, the increase of the F⁻ density was saturated at approximately 30 ms.

The F⁻ density obtained in the afterglow is plotted again in Fig. 8 as a function of the peak electron density of the discharge plasma for various modulation frequencies and duty factors. The CF₄ gas pressure and the instantaneous rf power were 2.5 mTorr and 1 kW, respectively. For the sake of reference, the F⁻ density

![Fig. 6 Relation between the F⁻ and electron densities. The electron density was controlled by changing the discharge duration. For the 10 ms operations (four open circles), the electron density was controlled by changing the rf power.](image-url)
Fluorine negative ions in high-density CF₄ plasmas

Fig. 7 Temporal variations of the F⁻ (a) and electron (b) densities in the pulse-modulated plasma with a modulation frequency of 10 kHz.

Fig. 8 Relation between the F⁻ and electron densities for various modulation frequencies and duty factors.

obtained for four rf powers with no modulation are also plotted. For the pulse-modulated case, the F⁻ density in the “last” afterglow (after the 10 ms discharge duration) is used in Fig. 8. It is found from Fig. 8 that the generation efficiency of F⁻ (the ratio nₐ₋/nₑ) in the pulse-modulated plasma was smaller than that in the continuously discharged plasma.

Figure 9 shows the integrated F⁻ density as a function of the pulse modulation frequency. The integrated F⁻ density was obtained by summing up the negative ion density during the entire discharge duration (10.2 ms). Since there was only one afterglow in the continuously discharged plasma, the integrated F⁻ density was a small value. For the pulse-modulated plasmas, the F⁻ density in each afterglow phase was lower than that in the continuously discharged plasmas as shown in Fig. 8. However, since the number of the afterglow increased with the modulation frequency, the modulation frequency had an optimum value of 10 kHz for obtaining the largest integrated F⁻ density.

4. Discussion

A well-known production process of F⁻ is dissociative electron attachment to CF₄ expressed by

\[
\text{CF}_4 + e^- \rightarrow \text{CF}_2 + F^-.
\]

In high-pressure (100-200 mTorr) parallel-plate discharges, it has been shown experimentally that the above reaction mainly produces F⁻ [8]. However, present experimental results in the low-pressure high-density helicon plasmas have several inconsistencies with the assumption that eq. (1) is the dominant production process of F⁻.
The first inconsistency is involved in Fig. 4. Figure 4 clearly shows that the efficient production of $F^-$ was obtained in the afterglow plasma. However, it is known that the reaction cross section of eq. (1) takes the largest value for an electron energy of approximately 7 eV [16]. The electron temperature of the present helicon plasma measured by an electrostatic probe was approximately 6 eV in the rf-on phase. After the termination of the rf power, the electron temperature rapidly decreased with a time constant of $\sim 5 \mu$s. Hence the experimental results showing the efficient production of $F^-$ in the low-temperature afterglow plasmas contradict the energy dependence of the reaction cross section of eq. (1). Secondly, Fig. 5 shows that the generation efficiency of $F^-$ was higher for the lower CF$_4$ gas pressure, which is also inconsistent with the assumption that $F^-$ is mainly produced by eq. (1). If the dissociative electron attachment to the parent gas is dominant, the greater production of $F^-$ is expected for the higher CF$_4$ gas pressure when the electron density is the same value, provided that the loss of F$^-$ by the collision with CF$_4$ is negligible. In our helicon plasma, the electron temperature was not strongly dependent on the gas pressure. Thirdly, the discharge duration dependence of the $F^-$ density shown in Fig. 6 cannot also be explained by eq. (1). Since the electron temperature reaches a steady-state value immediately after the initiation of the discharge, the same $F^-$ density is expected for the same electron density if the dissociative electron attachment to CF$_4$ is assumed as the dominant production process of $F^-$.

In reference to the experimental observations, we propose dissociative electron attachment to CF$_3$ given by

$$\text{CF}_3 + e \rightarrow \text{CF}_3^- \rightarrow \text{CF}_2 + F^-$$

(2)
as the dominant production process of $F^-$ in the low-temperature afterglow plasmas. The potential energy of the system of CF$_3 + F^-$ is only 0.03 eV higher than that of CF$_3$, and the potential curve of CF$_3$ has a crossing point with that of a compound state of CF$_3$ [17]. Therefore, if the electron colliding with CF$_3$ has an energy higher than 0.03 eV, the unstable compound state of CF$_3^*$ formed by electron attachment dissociates to CF$_2 + F^-$ with a high probability. Because of the small electron energy required for the reaction, this reaction is active in the low-temperature afterglow plasmas, while it is probably not so active in the discharge plasmas with an electron temperature of 6 eV since this reaction may have a large cross section for a narrow range of the small electron energy. The initial decrease of the electron density with a relatively slow decay time constant (32 $\mu$s in 10.00-10.02 ms) shown in Fig. 4 may correspond to the time duration where the electron temperature of the plasma drops to a value for the efficient reaction of eq. (2). After 10.02 ms, electron attachment to CF$_3$ becomes efficient under the low electron temperature, resulting in the rapid decrease of the electron density.

The discharge duration dependence of the $F^-$ density shown in Fig. 6 can also be explained by the electron attachment to CF$_3$. In our helicon-wave excited plasmas, it has been shown by the laser-induced fluorescence spectroscopy that the densities of CF and CF$_2$ reach steady-state values at a discharge time of approximately 1 ms in the continuously discharged plasma [18]. For a discharge duration shorter than 1 ms, the densities of CF$_3$ radicals are under the evolutions. Hence the production of $F^-$ by eq. (2) is inefficient for a short discharge duration. This explanation is also applicable for the low generation efficiency of $F^-$ at the beginning of the pulse-modulated discharge (0-2 ms in Fig. 7). The slow increase of the CF$_3$ density in the pulse-modulated plasma may be responsible for the gradual increase of $F^-$ after 2 ms for the constant electron density.

There are two reactions other than electron attachment to CF$_3$ as the production processes of $F^-$ in low-temperature afterglow plasmas; one is electron attachment to F atoms ($F + e \rightarrow F^- + h\nu$ and $F + e + e (M) \rightarrow F^- + e (M)$) and the other is dissociative electron attachment to F$_2$ ($F_2 + e \rightarrow F + F^-$. We recently measured the absolute F atom density in the CF$_4$ helicon plasmas by vacuum ultraviolet absorption spectroscopy [19]. The results show that the F atom density
was of the order of $10^{12}$ cm$^{-3}$ for the discharge conditions in the present experiments. For this F atom density and the rate constants available to date [20], the density of F$_2$ produced by the three-body reaction (F + F + M $\rightarrow$ F$_2$ + M) is expected to be very low in the low-pressure helicon-wave discharges. Hence the production of the large amount of F$^-$ observed experimentally cannot be explained by electron attachment to F$_2$. In addition, the reaction rate constant of electron attachment to F atoms is also too small to be the dominant production process of F$^-$. Major loss processes of F$^-$ in low-temperature afterglow plasmas are considered to be mutual neutralization with CF$_3^+$

$$\text{CF}_3^+ + \text{F}^- \rightarrow \text{CF}_3 + \text{F},$$

and associative detachment collision with CF$_3$

$$\text{CF}_3 + \text{F}^- \rightarrow \text{CF}_4 + \text{e}.$$ (4)

Referring to reaction rate constants [20], the former reaction is likely dominant in the high-density helicon-wave excited plasmas. Since a high positive ion density is maintained in the early afterglow, the reaction speed of eq. (3) is much faster than that of eq. (4). If the reaction shown in eq. (4) becomes dominant in the late afterglow, the decay time constant of the electron density should slow down due to the production of electrons from F$^-$. However, the decay curve of the electron density can be approximated well with a single exponential function after 10.02 ms.

With the assumption that mutual neutralization with CF$_3^+$ is the dominant loss process of F$^-$, it may be possible to explain the experimental result that the efficient generation of F$^-$ was obtained for a lower CF$_4$ gas pressure. The positive ion diagnostics carried out with the same time-of-flight mass spectrometer shows that, for the same electron density, the fractional abundance of CF$_3^+$ is higher for a higher CF$_4$ gas pressure [21]. For instance, for an electron density of $\sim 1 \times 10^{12}$ cm$^{-3}$, the ratio of CF$_3^+$:CF$_2^+$:CF$^+$ was 6:2:2 for an rf power of 0.7 kW and a CF$_4$ pressure of 2.5 mTorr, while the ratio was 9:0:1 for an rf power of 1 kW and a CF$_4$ pressure of 5 mTorr. Hence, if the reaction rate constants of the mutual neutralizations with other positive ions (CF$_3^+$ and CF$_2^+$) are smaller than that with CF$_3^+$, the higher composition of CF$_3^+$ can be responsible for the smaller generation of F$^-$ in the high-pressure discharge.

Finally, let us discuss effects of the pulse modulation of the rf power for the generation of F$^-$. For the same instantaneous rf power and the CF$_4$ pressure, the F$^-$ density appeared in the afterglow was lower in the pulse-modulated plasma than the continuously discharged plasma because of the lower electron density in the pulse modulated plasma. For the same electron density, the F$^-$ density was still lower in the pulse-modulated plasma as shown in Fig. 8, which may be due to the lower CF$_3$ density in the pulse-modulated operation. However, the F$^-$ density integrated over the discharge duration was higher in the pulse-modulated plasma than the continuously discharged plasma as shown in Fig. 9. Therefore, the pulse modulation of the rf power was not effective for increasing the generation efficiency of F$^-$ but for the increase of the sum total of F$^-$. The amount of F$^-$ dragged into the substrate in the etching process with the low-frequency (<1 MHz) rf bias may have a similar tendency with Fig. 9. In this way, improvements of the etching characteristics can probably be obtained by the pulse-modulated discharges.

5. Conclusions

In conclusion, we have shown the following.

(i) We have carried out negative ion diagnostics in helicon-wave excited high-density CF$_4$ plasmas by using a time-of-flight mass spectrometer.

(ii) Only fluorine negative ions were observed in afterglow plasmas as the negative ion species. No negative ions were detected in discharge plasmas.

(iii) The decay time constant of the electron density in the afterglow was shorter than 20 μs, which was one-order shorter than the ambipolar diffusion time of the system consisting of electrons and positive ions.

(iv) In order to explain the efficient production of F$^-$ in the low-temperature afterglow plasmas, dissociative electron attachment to CF$_3$ has been proposed as the dominant production process of F$^-$. The pulse modulation of the rf power was not effective for increasing the generation efficiency of negative ions but for the increase of the sum total of F$^-$ over the discharge duration.

ACKNOWLEDGEMENTS

Discussion with D. Hayashi and C. Suzuki is deeply acknowledged. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture.
References