Effect of Near-Threshold Ionization on Electron Attachment in Gaseous Dielectrics *

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It has been predicted that near-threshold ionization (NTI) in a gaseous dielectric inhibits the development of electron avalanche when the gaseous dielectric has a sufficient capability for low-energy electron attachment. The NTI leaves little energy for the primary and secondary electrons involved in the ionization; thus, both electrons can be captured by dielectric gas molecules without further ionization. A computational estimation indicates that this process can occur in SF_6.

KEYWORDS: gaseous dielectric, electron attachment, ionization, threshold, electron avalanche, sulfur hexafluoride

It would be a prevailing understanding that ionization in gaseous dielectrics is undesirable for electric insulation. However, there can surprisingly be an ionization process that inhibits the development of electron avalanche. An ionization collision at an electron energy near the ionization threshold can induce more electron attachments than compensates the increase in the number of electrons due to the ionization when the gaseous dielectric has a sufficient capability for low-energy electron attachment. The number of electrons rather decreases indirectly for ionization. Let us call such ionization and attachment processes 'near-threshold ionization' (NTI) and 'ionization-aided attachment' (IAA). SF_6, which is one of the most widely used representative gaseous dielectrics for electric power systems, is an example gas with an electronegativity adequate for the IAA. The IAA mechanism is interesting from the viewpoint of electron swarm dynamics in gas, and it may invoke innovative ideas for future gas insulation. In this paper, we explain the mechanism of the IAA, and point out its presence in the electron processes in SF_6.

Let us consider an ionization collision in SF_6 at the energy ϵ' near the ionization threshold $\epsilon_{\rm ion}$. The residual energy $\epsilon_{\rm res} = \epsilon' - \epsilon_{\rm ion}$ after the ionization collision is shared between the primary (colliding) and secondary (released) electrons. Their energies, ϵ_1 and ϵ_2, satisfy $\epsilon_1 + \epsilon_2 = \epsilon_{\rm res}$ and $\epsilon_1 : \epsilon_2 = \xi : (1-\xi)$ (see Fig. 1). Here, ξ is the energy division ratio ($0 \le \xi \le 1$). Because SF_6 has a large attachment cross section at low electron energies less than 1 eV,[1–3] it is probable that both of the primary and secondary electrons are captured before further ionizations when $\epsilon_{\rm res}$ is sufficiently small. In such a case, the number of free electrons in SF_6 decreases through the NTI and succeeding electron attachments.

The attachment capability of SF_6 can be quantified as the ratio $P_{\rm att}$ of electrons undergoing attachment before ionization. A Monte Carlo simulation has been carried out to calculate $P_{\rm att}$ as a function of the initial electron energy $\epsilon_{\rm ini}$, at which the electrons start their flights in SF_6. Here, $\epsilon_{\rm ini}$ corresponds to ϵ_1 and ϵ_2 for the primary and secondary electrons restarting their flights after the NTI. The collision cross sections of SF_6 have been obtained from refs. 1 and 2. The electric field reduced by the gas molecule number density, E/N, has been assumed to be 300–400 Td (1 Td = 10^{-17} V cm^2). This E/N range includes $(E/N)_{\rm critical} = 359.3 \pm 0.3$ Td,[3] at which the effective ionization coefficient $\bar{\alpha} = \alpha - \eta$ is zero (α and η are the ionization and attachment coefficients, respectively). At each $\epsilon_{\rm ini}$, 100 000 electrons have been traced.

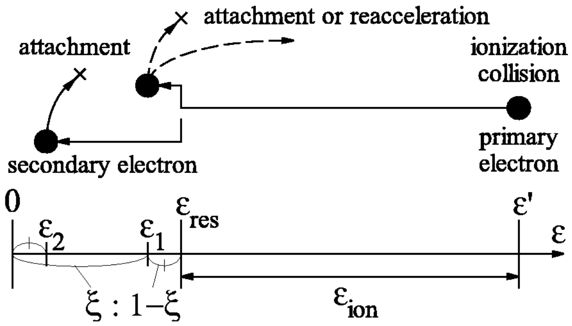

Fig. 1. Ionization collision at energy ϵ' and residual energy sharing between the primary and secondary electrons.

Figure 2 shows $P_{\rm att}$. In order to decrease the number of electrons by the IAA, at least one of the two electrons involved in an NTI must attach. The result $P_{\rm att} > 1/2$ represents that more than one-half of the electrons released with $\epsilon_{\rm ini}$ are captured by SF_6 without ionization on average. However, $P_{\rm att} = 1/2$ is not the critical value that guarantees a decrease in the number of electrons because the ionizations to be induced by the uncaptured electrons afterward are not always the NTIs compensable by the IAA. It is not easy to analytically specify the critical value of $P_{\rm att}$ and the range of $\epsilon_{\rm res}$ allowed for the NTI to guarantee a decrease in the number of electrons. Nonetheless, it is indicated that $P_{\rm att}$ of SF_6 at low $\epsilon_{\rm ini}$ values is sufficiently high to let the IAA work.

We show that the NTI in SF_6 reduces the number of electrons by another Monte Carlo simulation as a verification of the IAA theory explained above. We calculate the time-variant population $n(t)$ of the electrons originating from the initial 100 000 electrons undergoing ionization in the near-threshold energy range $\epsilon_{\rm l} \le \epsilon' \le \epsilon_{\rm u}$. For a clear demonstration of the decrease in the number of electrons after the NTI, we choose the lower and upper limits of the near-threshold range to be $\epsilon_{\rm l} = \epsilon_{\rm ion} = 15.8$ eV

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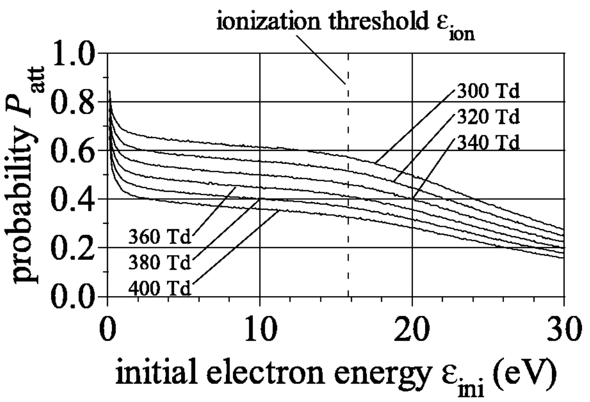

Fig. 2. Ratio P_{att} of electrons captured by SF_6 before ionization as a function of the initial electron energy ϵ_{ini}.

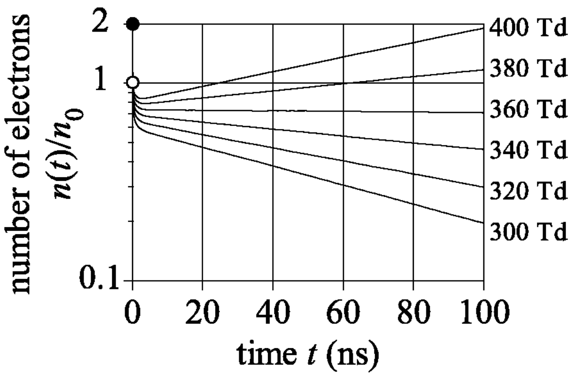

Fig. 3. Multiplication of electrons after NTI.

and $\epsilon_u = 15.9$ eV, respectively; ϵ_{res} to be shared by a pair of primary and secondary electrons is at most 0.1 eV. In order to take account of the onset of the ionization cross section q_{ion} of SF_6 from ϵ_{ion}, ϵ' is chosen as $\epsilon' = \epsilon_l + \sqrt{\chi}(\epsilon_u - \epsilon_l)$ with the uniform random number $0 \le \chi \le 1$. N is set at 3.54×10^{16} cm^{-3}, assuming a gas pressure of 133 Pa (1 Torr) at 0°C. Because the probability density function for ξ is unknown, we assume that ξ distributes uniformly between 0 and 1.

Figure 3 shows $n(t)$ after the NTI. In the beginning, the number of initial electrons n_0 is 100 000 at $t = 0$ ($\circ$ in Fig. 3), and the electrons multiply instantly from n_0 to $2n_0$ by ionization (from $\circ$ to $\bullet$). At this time, most of the energy of the primary electrons is lost as the ionization energy to release the secondary electrons. The electron energy after the NTI is low; thus, more than one-half of the electrons are captured by SF_6 in about 0.2 ns. Then, after a few nanoseconds of relaxation, the electrons establish an exponential growth.

The key point of this result is that the exponential growth of $n(t)$ starts effectively from electrons less than n_0. The IAA mechanism that one NTI induces more than one electron attachment has been verified. The NTI in SF_6 has a function to reduce the number of free electrons. This finding is also supported by the result of an additional calculation by a propagator method,[4] which is a numerical technique for solving the Boltzmann equation for the electron energy distribution. When we suppress the NTI of SF_6 in the energy range 15.8–15.9 eV forcedly, $(E/N)_{critical}$ becomes slightly lower while α decreases. This is due to the disappearance of the IAA. The decrease in η due to the disappearance of the IAA is greater than that in α due to the elimination of the NTI, which makes $\bar{\alpha} = \alpha - \eta$ higher.

The NTI that induces the IAA in SF_6 can occur in a limited energy range. However, as long as $q_{ion} \neq 0$ nearby ϵ_{ion}, ionization in SF_6 involves the NTI to some extent. This indicates the presence of the IAA in SF_6 as an actual electron process.

In conclusion, we have explained the mechanism of the IAA and demonstrated the time-variant population of electrons involved in the NTI in SF_6. The increase in the number of electrons due to the NTI in SF_6 is compensated by the succeeding decrease in the number of electrons due to the attachment of the primary and secondary electrons. It has been indicated that the ionization process in SF_6 involves the IAA, which contributes to the suppression of electron avalanche in SF_6.

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