# A Comment on Formative Time Lag of Gaseous Breakdown

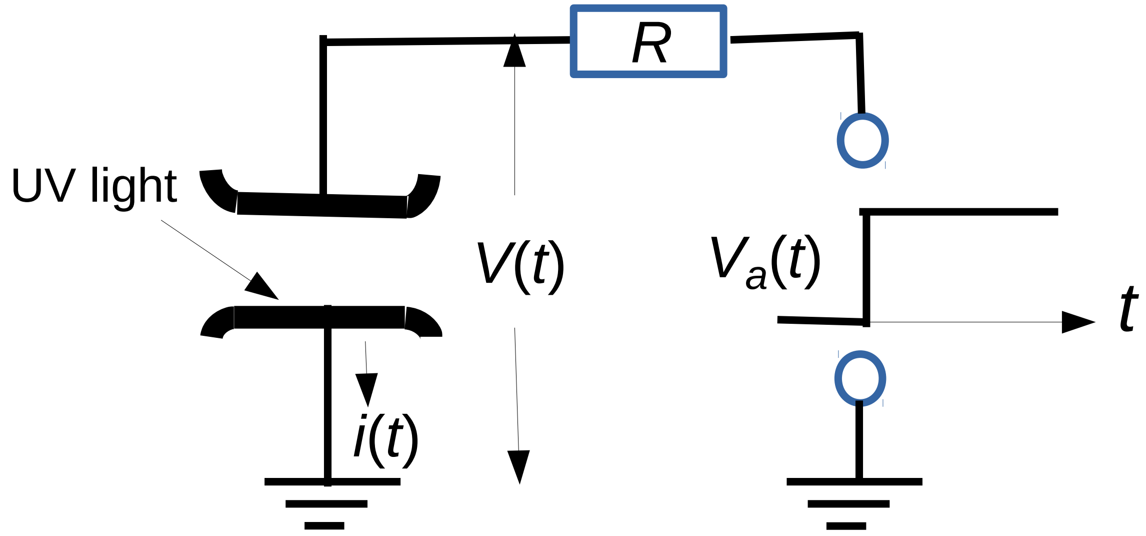
H.Mase

Professor Emeritus of Ibaraki University

The breakdown starts at the time when the electron density near the anode increases up to the critical density by ionization growth in the electron avalanche.

We discuss the effect of initial electrons on the formative time lag.

# Circuit for Measurement of Time delay in Gaseous Discharge

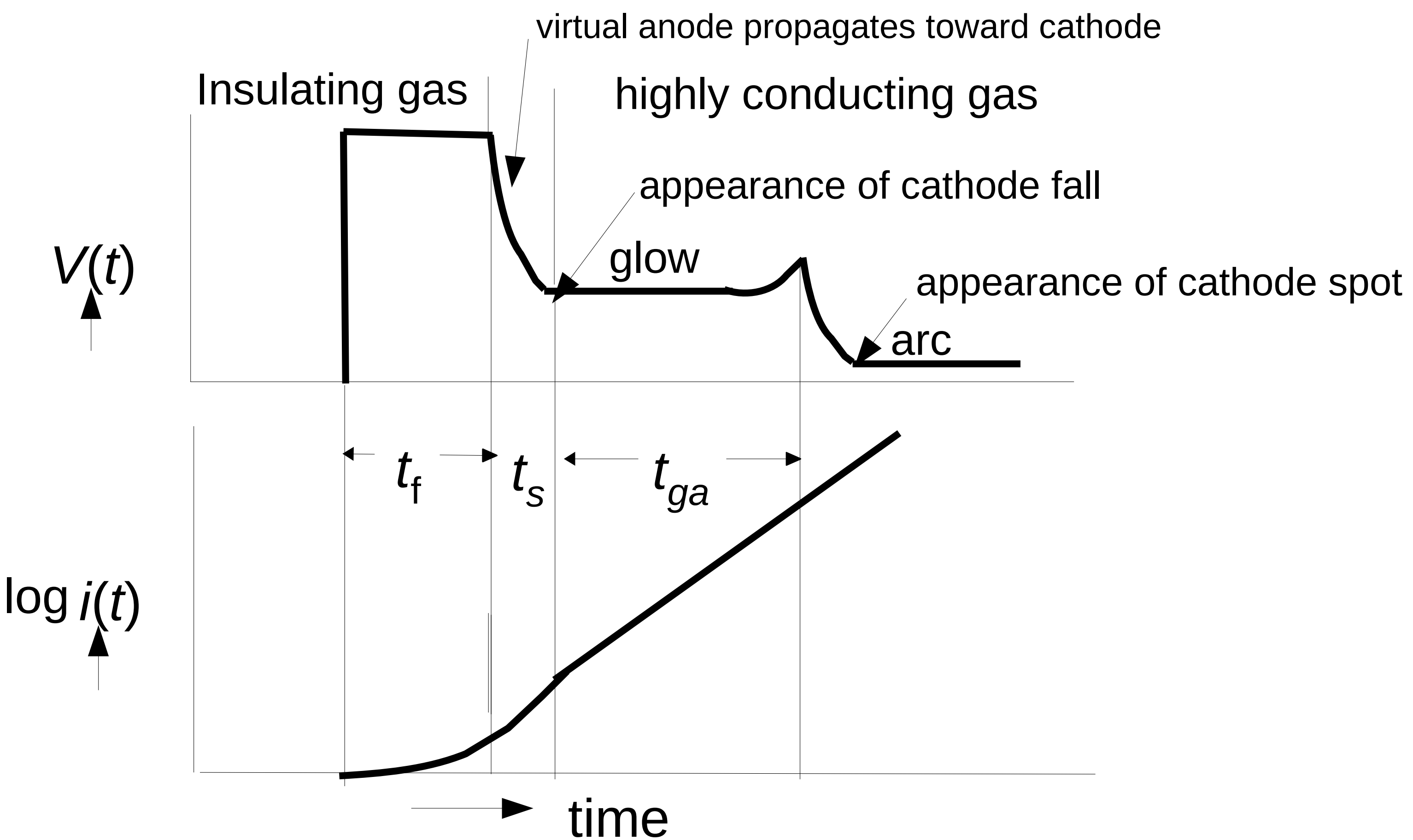



Observation of V(t) and i(t) by using an oscilloscope

In order to avoid statistical time delay caused by the initial electron generation, the cathode is irradiated with UV light.

# Time Lags of Electric Discharge in Gases

## -Time Sequence of Events and Traces of *V*(*t*) & *i*(*t*)-




$t_f$ : formative time lag, time to the just starting breakdown by applying step voltage.

$t_s$ : time delay until when the streamer reaches the cathode front and glow discharge starts.

$t_{ga}$ : time of glow-to-arc transition

*sometime formative time lag means $t_f + t_s$

# Deposition of Ion and Electron Space Charges across electrodes by Ionization Growth for $t \lesssim t_f$ (1/2)

Ion space charge

ion transit time $\tau_\iota = d/v_i >> t_f$

$$\frac{d\,n_i}{dt} d = \frac{v_e}{\lambda_i} n_i d - n_i v_i \approx \frac{v_i}{\lambda_i} n_e d > 0$$

Electron space charge

for $t < t_f$, electron transit time $\tau_e = d/v_e < t_f$

$$\frac{d\,n_e}{dt} d = \frac{v_e}{\lambda_i} n_e d - n_e v_e \approx 0$$

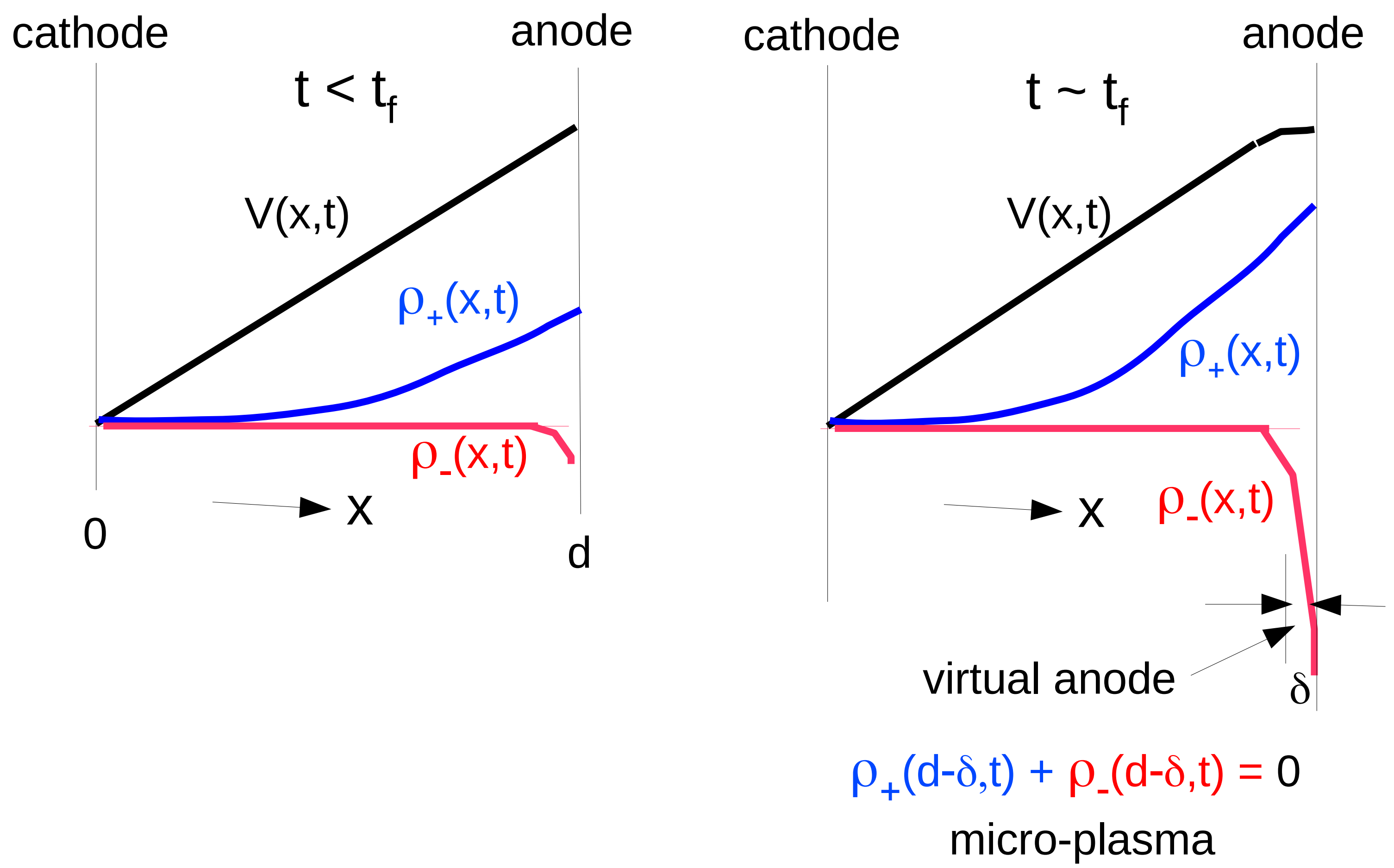
for $t \sim t_f$, electrons are decelerated by distorted field by ion space charge near the anode.

$$\frac{d\,n_e}{dt} \delta \approx \frac{v_e}{\lambda_i} n_e \delta > 0$$

where $\delta$ is thickness of micro-plasma which appeared near the anode at the time of just starting breakdown.

# Deposition of Ion and Electron Space Charges across electrodes by Ionization Growth for $t \lesssim t_f$ (2/2)

- Spatial Distribution of Ion and Electron Space Charges -



# Derivation of Formative Time Lag $t_f$ (1/4)

In the previous report we discussed the critical electron density at the time of just starting breakdown. The critecal electron density is given by the following Equation* (see appendix B,C).

$$n_e^* = \frac{\varepsilon_0}{e}\left(\frac{e\phi_i}{T_{eV}}\right)\frac{\varphi_i}{\lambda_{i0}^2}p^2$$

Formative time lag could be given by the time when the electron density is increased up to a critical electron density.

$$\frac{dn_e}{dt} = \frac{v_e}{\lambda_i}n_e \quad , \qquad n_e(t) = n_{e0}\exp\left(\frac{v_e}{\lambda_i}t\right)$$

Formative time lag is expressed as follows:

$$t_f = \frac{\lambda_i}{v_e}\ln\left(\frac{n_e^*}{n_{e0}}\right)$$

where $v_e$ and $\lambda_\iota$ are electron velocity and mean ionization length, respectively.

* The critical electron density was explained in the previous report.

# Derivation of Formative Time Lag tf (2/4)

## - Shortest formative Time Lag -

$$t_f = \frac{\lambda_i}{v_e} \ln\left(\frac{n_e^*}{n_{e0}}\right)$$

Formative time lag essentially depends on $\lambda_i/v_e$ and rate of electron growth $(n_e^*/n_0)$.

If the breakdown is initiated in just one of the electron avalanche, $(n_e^*/n_{e0})=\exp[d/\lambda_i]$, $t_f$ becomes the shortest time.

$$t_{f\,min} = \frac{\lambda_i}{v_e} \ln\left(\exp\left(\frac{d}{\lambda_i}\right)\right) = \frac{d}{v_e}$$

where d is gap length. Electron velocity $v_e$ is proportional to $[(V_a/d)\lambda_i]^{1/2}$ Therefore, $t_{fmin}$ would be decreasing with square-root of over voltage $(V_a/V_{BD})=[V_a\lambda_i/\phi_i d]$ , where $V_{BD}$ is static breakdown threshold.

In order to achieve a minimum formative time lag the density of initial electrons is required to the following formula.

$$n_{e0} = n_{e0}^* \geq n_e^* \exp\left(\frac{-d}{\lambda_i}\right) = \exp\left(\frac{-d}{\lambda_i}\right) \frac{\varepsilon_0}{e} \left(\frac{e\phi_i}{T_{eV}}\right) \frac{\varphi_i}{\lambda_{i0}^2} p^2$$

# Derivation of Formative Time Lag $t_f$ (3/4)

## - Dependency of Electron Growth ($n_e^*/ n_{e0}$) -

In the case of $n_{e0} < n_{e0}^*$, it is necessary to release additional electrons on the cathode by impact of photons from the multiple avalanches. ,

If the breakdown starts after N times of avalanches, $n_e^*/ n_{e0}$ is given by

$$\frac{n_e^*}{n_{e0}} = \left(\frac{1-M^N}{1-M}\right) e^{\frac{d}{\lambda_i}}, \qquad M = \gamma_p e^{\frac{d}{\lambda_i}}$$

where $\gamma_p$ is the generation rate of initial electrons by photon radiation from excited atoms in the avalanche .

If M ~ 1 (M = 1 is the self-sustaining condition), the above equation could be expressed as follows (see appendix D)

$$\frac{n_e^*}{n_{e0}} \sim N e^{\frac{d}{\lambda_i}}$$

Required amount of initial electrons and formative time lag for start of breakdown are

$$n_{e0} \geq \left(\frac{1}{N}\right) n_e^* e^{\frac{-d}{\lambda_i}}$$

$$t_f \leq N \frac{d}{v_e} = N * t_{f\,min}$$

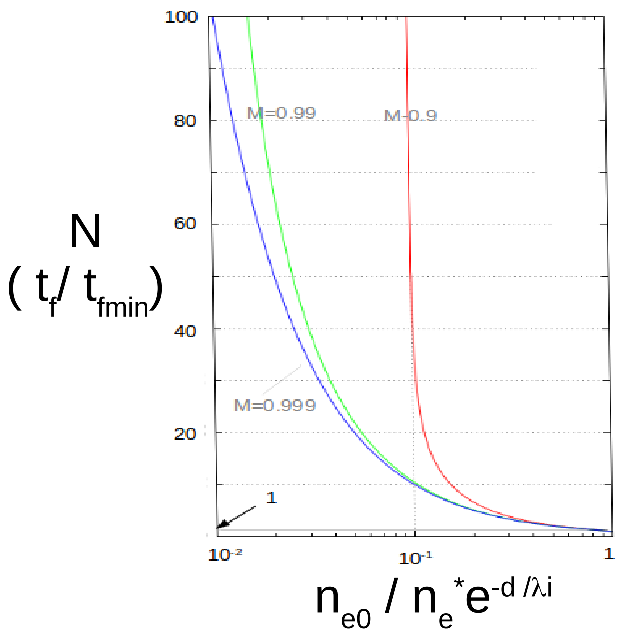
# Derivation of Formative Time Lag $t_f$ (4/4)

## - Dependency of Electron Multiplication $M=\gamma_p e^{d/\lambda i}$ -

If the breakdown starts after N times of avalanches, $n_{e0}$ is given by

$$n_{e0} \geq \left(\frac{1-M}{1-M^N}\right) n_e^* e^{\frac{-d}{\lambda_i}} \qquad M=\gamma_i e^{\frac{-d}{\lambda_i}}$$

Following figure shows the relationship between $n_{e0}$ and N in the range of $0.9 < M < 0.999$. When $M = 0.999$ and $n_{eo} \sim 10^{-1} n_e^* e^{-d/\lambda\iota}$, we find that it appears 10 times of avalanches for starting breakdown. If $M = 0.9$, the breakdown does not occur in the range of $n_{e0} < 10^{-1} n_e^* e^{-d/\lambda i}$. The breakdown does not occur in the the left region of the curve.




$n_e^*$: critical electron density at the time of just starting breakdown

# Summary

The breakdown starts at the time when the electron density near the anode increases up to the critical density $n_e^*$ by the electron avalanche. We discuss the effect of initial electrons on the formative time lag.

If the breakdown is initiated in just one of the electron avalanche, the formative time lag takes the shortest value of $t_f = d/v_e$, and the initial electron density is required to be more than $n_{e0}^* = n_e^* \exp[-d/\lambda_i]$ , where d, $v_e$ and $\lambda_i$ are gap length, electron velocity and mean ionization length, respectively.

In the case of $n_{e0} < n_{e0}^*$, the lack of initial electron density is necessary to supplement with the secondary emission by the photons from the multiple avalanches. The formative time lag is determined by the number of repetitions of the avalanches.

**Appendix A**

# Brief Comment on Other Time Delay in Gaseous Discharge

- $t_s$ : time delay until when the streamer (virtual anode) reaches the cathode front and the glow discharge just starts.

In the phase of $t > t_f$ , $t_s$ strongly depends on the impedance of discharge circuit and power supply. Specific breakdown phenomenon occurs in the case of the very low impedance circuit and then $t_s$ could be expressed as $t_s \sim d/v_s + d_c/v_i$ , where $v_s$ , $d_c$ and $v_i$ are the propagation seed of streamer, cathode sheath thickness and ion velocity, respectively. In the In the process of breakdown, the electron emission by ions that bombard on cathode is to play an important role.
$t = t_f + t_s$ can also be referred to as the tune-on delay time of insulating gap and same times $t = t_f + t_s$ is treated as formative time lag.

- $t_{ga}$ : glow-to-arc transition time.

In the phase of $t > t_f + t_s$ , $t_{ga}$ also strongly depends on the impedance of discharge circuit and $t_{ga}$ is mainly determined by the thermal properties of discharge system. The phenomenon of glow-to-arc transition is very complex.

**Appendix B**

# A Hypothesis for the Appearance of Micro-Plasma at Anode Near Region

$$E^{*} = \frac{\phi_i}{\lambda_i} = \frac{T_{eV}/e}{\lambda_D}$$

$T_{eV}$ electron temperature in eV

$\lambda_D$ Debye shielding length

$E \approx 0$ in the plasma column

$E^*$ would be shielded electrically by the polarization of plasma particles. It is best that $T_{ev}$ should be confirmed theoretically by the plasma balance equation. Usually $T_{eV}$ is in the range of several eV.

**Appendix C**

# Critical Electron Density ne*
# at Just Starting Breakdown in Gases

$$\frac{\phi_i}{\lambda_i} = \frac{T_{eV}/e}{\lambda_D}, \qquad \frac{1}{\lambda_D} = \left( \frac{n_e^* e^2}{\varepsilon_0 T_{eV}} \right)^{1/2}$$

$$n_e^* = \frac{\varepsilon_0}{e} \left( \frac{e\phi_i}{T_{eV}} \right) \left( \frac{\phi_i}{\lambda_{i0}^2} \right) p^2$$

$$\frac{e\phi_i}{T_{eV}} \approx 10, \quad \phi_i = 10\ \mathrm{V}, \quad \lambda_i = 5 \times 10^{-4} / P[\mathrm{atm}] \quad \mathrm{cm}$$

$$n_e^* \approx 2 \times 10^{14}\, p^2 \ \ \mathrm{cm}^{-3} \qquad p \ \ \text{in atm}$$

**Appendix D**

# Derivation of $n_e^*/n_{e0} \sim Ne^{d/\lambda_i}$

$$\frac{n_e^*}{n_{e0}} = \left(\frac{1-M^N}{1-M}\right) e^{\frac{d}{\lambda_i}}, \qquad M = \gamma_p e^{\frac{d}{\lambda_i}} < 1$$

$$M^N = \exp\left(\left(\ln(M)\right)N\right) = 1 + \left(\left(\ln(M)\right)N\right) + \frac{1}{2}\left(\left(\ln(M)\right)N\right)^2 + \quad \sim 1 + \left(\left(\ln(M)\right)N\right)$$

$$\ln(M) \sim 1 - M$$

$$\frac{1-M^N}{1-M} \sim \frac{1-\left(1+\left(\left(\ln(M)\right)N\right)\right)}{1-M} \sim N$$