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ON THE SPARK FORMATION IN THE SPARK CHAMBER

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The spark formation in the spark chamber is discussed assuming that the streamer theory is applicable in the pulsed field across a relatively high pressure gas. Following the time elapsed since the electrons are created by an incident charged particle the discussions are presented. The streamer theory introduced by Meek and Raether is briefly described.

1. Introduction.

The appearance of sparks in the spark chamber is affected by many parameters viz. the gas used (the sort, the pressure, and the contamination of the air or organic vapours); the rise time, the amplitude and the duration of the pulse; the time between the path of the particle and the application of the pulse; the multiplicity and the spatial separation of incident particles; the angle between the path of the particle and the direction of the electric field; the number of ion pairs per unit of the path of the particle, etc.

It is experimentally and theoretically clear that the sparks in the usual spark chamber are initiated by electrons, not by ions. In this paper the behaviour of these electrons is discussed following the time elapsed from the moment of the creation of electrons up to their disappearance through the stage of the spark formation.1) In the description on the gaseous discharge we follow the similarity principle. Thus the knowledge obtained in the low pressure discharges can be applied to the high pressure discharges, because it is experimentally found that some combinations of parameters can be deduced and the property of discharges can be fixed by these groups of parameters and others, for example Paschen's law and the ionization by the accelerated electrons. Here we fix the pressure of gases to an atmospheric pressure.

2. The pre-pulse stage

a) The number of original electrons.

The number of original electrons can be estimated by the process of ionization of charged particles.$^{2)}$ The blobs which give locally dense electrons are also produced, but the number of blobs per unit track length is very small. Assuming the energy of δ-ray is enough to produce more than ten electrons, the number of such δ-rays is less than one per cm. Therefore we can neglect the δ-ray production. Table I gives the estimated number of electrons produced by the relativistic particle.

The energies of electrons emitted are higher than the thermal energy. Electrons lose their energies due to collisions with gas atoms and are thermalized after the order of 10 ns*.

b) The diffusion of electrons.

Owing to the thermal agitation the position of electrons is varied. We can assume that the original electrons are on the trajectory of the particle. When the electric field such as the clearing field is not applied, the mean lateral displacement of electrons is given by

$$\ell = \sqrt{2\,Dt},$$

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* The mean energy of ionized electrons is of the order of 10 eV. The elastic collision frequency of these electrons is $10^{11} \sim 10^{12}$/s. The energy loss per collision is given by $\Delta\epsilon = -\frac{2m}{M}\,\epsilon$, where ϵ is the electron energy and m and M are the masses of the electron and the atom, respectively.

where D is the diffusion coefficient of electrons depending on the electron energy and t is the time elapsed. At $t = 1 \mu s$, ℓ is the order of magnitude of 1 mm. The values of D for various electron energies are listed in Table II.

c) The drift velocity of electrons.

The original electrons diffuse away from their initial places owing to their random walk. The mean velocity, ν_r, of thermal agitation is

$$\bar{\epsilon} = \frac{3}{2} KT_e = \frac{1}{2} m \bar{\nu}_r^{\,2} ,$$

and $\bar{\nu}_r \simeq 1 \times 10^7$ cm/s at $T_e = 300^\circ$ K.

When the electric field is applied, the electrons drift to the anode. The electrons get the energy from the field, therefore $\bar{\nu}_r$ increases. If the field intensity, E , is not so high, the drift velocity is proportional to E. Owing to the random walk the drift velocity is less than the agitation velocity. In other words the velocity of the centre of gravity in the direction of the field is defined as the drift velocity. In the higher field such as the pulsed field applied to the chamber, the drift velocity is proportional to $\sqrt{E}$. The values of the drift velocity for various E are listed in Table II and the values of the mean agitation velocity are also listed for comparison.

In the clearing field the electrons move towards the anode with the drift velocity, and diffuse away in the lateral direction with the diffusion velocity. When the polarity of the clearing field is the same as that of the pulsed field, the effective number of electrons necessary for sparks becomes less than in the case of the anti-polarity. This correlates to the memory time of the chamber.

d) Recombination and negative ion formation.

The electrons disappear owing to the process of recombination and negative ion formation. The density of original ion pairs is very low so the probability of recombination is quite negligible. In the pure noble gases the process of electron capture is also negligible. However, when the chamber is contaminated by air or organic vapours the probability of electron capture cannot be neglected because the cross section for negative ion formation is very large. For example the oxygen molecule becomes a negative ion with the probability of $\sim 10^{-4}$ per collision. The contamination of the oxygen molecule reduces the survival probability of electrons in the gap. 1% oxygen shortens the lifetime of electrons to 10 μs and 10% reduces the lifetime to 1 μs.

3. The pulse stage.

a) The streamer theory of the spark.

This new theory of the spark named the "streamer theory" was introduced by Meek[3)] and independently by Raether[4)] as a consequence of experimental results on spark development. Here a brief outline of the theory is presented.

Consider the stationary electric field of E (volts per cm) across a gap of d (cm) between parallel plane electrodes in a gas at a pressure of p (mm Hg). An electron leaving the cathode or produced in the gas will be accelerated in the applied field and ionize the gas molecules. The additional electrons formed will cause further ionization. At dx of a path of n electrons in the direction of the field the number of electrons created is given by

$$dn = n \alpha \, dx$$

where α is the first Townsend ionization coefficient which is defined as the number of new ion pairs produced by an electron moving through 1 cm in the direction of the field. The number of electrons created after a path x is $\exp(\alpha x)$. The process is rapidly cumulative and is termed an "electron avalanche".

The electrons move to the anode with the drift velocity. As the drift velocity of positive ions is about two orders of magnitude slower than that of electrons, the positive ions may be considered stationary and the avalanche develops across the gap as a cloud of electrons, leaving behind positive ions. The electrons and ions are concentrated at the head of the avalanche in a sphere of radius ρ. The radius ρ is given by the lateral distribution of electrons, that is ,

$$\rho = \sqrt{4\ Dt} = \sqrt{4\ Dx/\nu_{drift}} .$$

The space charge of the avalanche distorts the applied field in the gap. The space charge field increases the magnitude of the field along the axis and also creates a radial field to the axis. When the space charge field becomes of the order of the applied field, subsidiary electron avalanches are produced in the region where the field is enhanced in the direction of the applied field, and are accumulated into the original avalanche and produce a conductive region. The subsidiary avalanches are initiated by photo-electrons because some of the excited atoms in the main avalanche emit ultra-violet lights with lifetime of the order of 0.1 μs. The conductive region thus produced is called "streamer". The streamer can quickly spread towards both electrodes due to the rapid accumulation of additional avalanches.

The critical condition for the transition from an avalanche into a streamer is given as follows; assume that the ions are contained in a sphere of radius ρ. The space charge field is given by

$$E_r = q_e/r^2 ,$$

where q is the number of ions in the sphere and e is the electron charge. q is expressed by

$$q = \frac{4}{3}\pi\rho^3 N ,$$

where $N = \alpha e^{\alpha x}/\pi\rho^2$ is the density of ions at the end of a path. Then the condition obtained is

$$E_r = \frac{4}{3}\,\frac{\rho\alpha e^{\alpha x}}{r^2} = E_{ext} , \text{ at } r = \rho \qquad \ldots\ldots\ldots\ldots \text{(A)}$$

where $\rho = \sqrt{4\,Dt} = \sqrt{4\,Dx/v_{drift}}$.

Let us consider next the condition necessary for streamer development[5)]. The total number of photons emitted which can produce photo-electrons may be proportional to the number of ions and is defined by

$$fq = \frac{4}{3}\, f\rho\alpha e^{\alpha x} .$$

The number of photons which can pass through the region where a new avalanche should be initiated is

$$\frac{4}{3}\,\frac{\Delta\Omega}{4\pi}\, f\rho\alpha e^{\alpha x} .$$

The probability of the emission of photo-electron is given by $\exp(-\ell/\lambda)$ where λ is the production mean free path. When the number of additional avalanches is more than 1, the streamer can propagate. Thus, we obtain the critical condition as

$$\frac{\Delta\Omega}{3\pi}\, f\rho\alpha e^{\alpha x} e^{-\frac{\ell}{\lambda}} \geqq 1 .$$

Owing to the lack of knowledge on f and λ we cannot precisely estimate the number of photo-electrons.

In the case where $E_{ext} = 10$ Kv/cm is applied in a rare gas such as He or Ne, the electron avalanche reaches the critical condition at the end of ~ 4 mm path and has about 10^8 ion pairs in its head which is a sphere of radius of ~ 0.5 mm. In other words the critical condition is satisfied at ~ 10^{-7} sec after an original electron is accelerated. The streamer propagates faster and in the order of 10^{-8} sec the streamer bridges across the electrodes and makes a spark.

The time elapse for satisfying the critical conditions corresponds to the time lag of breakdown. It can be considered that the streamer propagation is faster because the subsidiary avalanches are not necessary to satisfy the critical condition (A).

Next we must consider the fluctuation of the number of ion pairs in the avalanche[6)]. The probability that a given electron has grown to an avalanche of n electrons at a path of x is presented by $p(n,x)$. The probability that the electron has not ionized at all is given by

$$p\,(1,x) = \exp\,(-\int_0^x \alpha dx)$$

where α is the number of electrons ionized at a path of dx.

$$p(2,x) = \exp(-\alpha x)[1-\exp(-\alpha x)]$$

is the probability that only one ionization will occur, i.e. only two electrons will exist at x.

$$p(3,x) = \exp(-\alpha x)[1-\exp(-\alpha x)]^2$$

is the probability that the ionization will occur twice, i.e. three electrons will exist at x. Thus we can get the probability $p(n,x)$ as

$$\begin{aligned} p(n,x) &= \exp(-\alpha x)[1-\exp(-\alpha x)]^{n-1} \\ &= \frac{1}{\bar{n}}\,(1-\frac{1}{\bar{n}})^{n-1} \\ &\simeq \frac{1}{\bar{n}}\exp\,[-n/\bar{n}]\ , \text{ for } \bar{n} \gg 1\ , \end{aligned}$$

where the mean number of electrons produced is

$$\bar{n} = \sum_{n=1}^{\infty} n\ p(n,x) = \exp\,(\alpha x)\ .$$

b) <u>The interpretation of sparks in the chamber.</u>

The streamer theory described above is introduced for the spark development in the low gas pressure and in the stationary electric field. The spark chamber, usually filled with a rare gas at an atmospheric pressure, is operated by a triggered pulse of a very short duration. Here we assume that a spark formation in the chamber is also predicted by the streamer theory.

The applied field intensity varies with the time. Usually it rises to the maximum value with the rise time and decreases exponentially with a certain time constant. Therefore the parameters, i.e. the drift velocity of electrons and the ionization coefficient, vary with the time. In the pulsed field the critical condition for the streamer formation is satisfied at a certain moment, t_c, after the pulse is applied, that is $E_r(t_c) = E_{ext}(t_c)$. After t_c the space charge field intensity becomes higher than the applied field intensity because the latter decreases with the time. Therefore to make a spark breakdown the additional electron avalanches initiated by photo-electrons play an important role. In this case the field in which the additional avalanches develop is kept by the space charge of the original streamer. Comparing the time lag of spark formation with the time constant of the applied pulse this may be likely[7)].

In a spark chamber, original electrons are multiple even if one particle passes through, and they are nearly on a line of its particle trajectory. The spark formation may be affected by the spatial distribution of electron avalanches or streamers in a gap, because a space charge of avalanche interacts together.

By a certain operational condition we can observe a spark parallel to a particle trajectory at an angle of up to 60° with the normal of the electrode[8)]. But almost all pictures taken with chambers which were used in high energy experiments show that one spark corresponds to one particle, but it is perpendicular to the electrode not parallel to a particle trajectory. These two different types of spark formation are only caused by operational conditions of spark chambers, for example, relatively large numbers of original electrons, a fast rise time and relatively high amplitude of a pulse can produce a spark parallel to a trajectory. Moreover in a chamber operated in a normal condition one particle corresponds to more than one spark in a gap when an angle between a trajectory and the normal of the electrode is larger than 20° and the number of sparks has a relation with that angle. These different spark formations can be explained by the operational conditions, especially the amplitude of a pulse and by spatial distribution of electron avalanches.

Let us consider a simple case that two original electrons are on a line, which has an angle θ with the normal of the electrode, and a distance of two electrons along the line is ℓ.[*] At a moment when both electron avalanches satisfy the critical condition defined by Eq (A) separately, the field configuration around two avalanches should be considered, because the streamers propagate in the field produced by space charges. We can assume that the electrons are concentrated in a semi-sphere at the tip of the avalanche and the ions are mainly in the other semi-sphere whose radius ρ is given by Eq (A).

When $\ell \leqq 2\rho$, two avalanches overlap and produce a single streamer even if the avalanches reach the critical condition after relatively long paths and θ takes any value. This new streamer may propagate parallel to a line on which there are original electrons.

When $\ell \simeq 3\rho$, the space charge field intensity between the heads of two avalanches is nearly equal to the external field intensity if avalanches reach the critical condition after very short paths, and the streamer may propagate along the direction of the space charge field, because the space between two avalanches is more irradiated by ultra-violet light than the tips of avalanches and then photo-electrons are more likely to be produced in this space. The direction of the space charge field is nearly parallel to a line on which there are original electrons. When avalanches reach the critical condition after long paths, the ion clouds which are distributed in a conical shape may distort the field between avalanches and the space charge field intensity may be less than the external field intensity. Thereby, the streamer may not propagate in the space between two avalanches.

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[*] See Fig. 1.

When $\ell > 3\rho$, the space charge field intensity between the avalanches cannot be equal to the external field intensity. Therefore the streamer may propagate separately along the axis of each avalanche.

In the case of multi-electrons, as in the practical chamber, we must take account of the fluctuation of the development of avalanches. As described above, about one third of the avalanches may reach the critical condition faster than the other two thirds. The advancing avalanches may disturb the development of neighbouring avalanches. So we may consider only these advancing avalanches and for the field configuration between avalanches we can take ℓ as the distance between two advancing avalanches.

In principle we can obtain a track parallel to the particle trajectory at any angle but when the angle θ is larger than 60° that is not easy except with the application of a high frequency field.

Finally, it should be noted that the sparks which produce the tracks are the phenomenon which is nearly saturated by electron ion pairs owing to gaseous discharge mechanism and so their application for the measurement of primary ionization may give errative results. In this paper, moreover, spark formation in a chamber admixed with organic or halogen vapours is not discussed.

c) On the effect of mixture of rare gases.

When a small amount of argon is admixed in neon gas, the breakdown voltage is reduced. This phenomenon called Penning effect is explained as follows. The potential of the lowest excited state of neon, metastable, is slightly higher than the ionization of argon. When metastable state neon atoms collide with neutral argon atoms, argon atoms can be ionized.

When an electron is accelerated in the gap, the processes of

$$e + N_e \rightarrow N_e^+ + e + e \qquad \text{.........} (1)$$

$$e + A \rightarrow A^+ + e + e \qquad \text{.........} (2)$$

$$e + N_e \rightarrow N_e^* + e \qquad \text{.........} (3)$$

are predominant, but the process of

$$N_e^* + A \rightarrow A^+ + N_e + e \qquad \text{.........} (4)$$

increases the number of ionized electrons. By these processes the total number of electrons is higher than in a pure gas. Therefore the breakdown voltage is reduced. In a DC field 0.1 % of argon in neon gas gives a minimum voltage.

However in a pulsed field the optimum percentage of argon varies with the width of the pulse. In a short pulse field the direct ionization processes, (1) and (2), are predominant, because the process (4) takes a longer time. But when 10% of argon is admixed, the process (4) becomes comparably equal to the processes (1) and (2). In the case of 0.1 μs width of the pulse, 20% of argon in neon gas gives a minimum breakdown voltage.[10)]

4. The post-pulse stage

i) The dissociative recombination.

Observing the light from the spark in sequence of time we can notice that after the high electric field is removed the light is still emitted and the intensity has a maximum. This phenomenon is called "afterglow". In the case of neon and argon mixture (neon is the main gas) the light emitted in the pulse stage mostly corresponds to the neon spectrum lines, and the intensity of the argon lines is not proportional to the argon percentage of the mixture.

In the case of a 10% argon mixture, the intensity of argon line is less than 1%. However, the lights emitted in the post-pulse stage correspond to the argon lines, and the intensity and the time when the intensity reaches a maximum, are related to the percentage of argon admixture. In the case of 10% argon, the integrated intensity of argon lines is several per cent of that of neon lines and the maximum intensity of argon lines occurs 20 ~ 70 μs after the pulsed field is removed.

The separate light emission from the mixture of rare gases can be explained as follows. In the pulse stage the lights are emitted from the excited atoms. The number of excited atoms produced by electrons is related to the energy of electrons. Just after the electric field is taken off, the electrons and ions are concentrated in the spark region with very high density and the mean energy of electrons is also high. So the recombination between ions and electrons is unlikely even if the densities are high. The electrons lose their energies by the collisions, the positive ions collide with neutral atoms and form the molecular ions, for example $(N_eN_e)^+$ and $(A\ N_e)^+$. The cross-section of the molecular ion formation such as $(A\ N_e)^+$ is larger than that of $(N_eN_e)^+$ owing to the binding energy. The electrons can dissociate such molecular ions easily and emit the light which corresponds to argon line because of the difference of the energy between argon and neon when excited.

ii) The ambipolar diffusion.

The density of electrons and ions decreases, owing to the process of the dissociative recombination but the densities are still high. Therefore the electrons cannot move freely but diffuse being trapped by the positive ions. This diffusion is called "ambipolar diffusion" and is slower than free diffusion. At this stage the number of ions and electrons decrease, owing to the recombination process.

iii) The free diffusion.

After the density of ions and electrons decreases to a certain value, the external electric field such as a clearing field can act on the electrons and ions. Then the electrons move toward the anode and disappear.

5. Summary

i) The memory time.

This mainly depends on the clearing field and its polarity to the pulsed field. As described in 3. a) the region near the anode is insensitive. The memory time, T is estimated as follows, assuming that only one electron in the sensitive region can produce a spark, here d is the gap distance, a is the width of the insensitive region and ν_{drift} velocity of electrons.

a) The same polarity of the field

$$T = \frac{d-a}{\nu_{drift}} \text{ sec.}$$

In the case that d = 1 cm, the clearing field is 100 v/cm and the max. field intensity of the pulse is 10 Kv/cm, $T \simeq 1$ µs.

b) The anti-polarity

$$T = \frac{d}{\nu_{drift}} \text{ sec.}$$

When d = 1 cm and the clearing field is 100 v/cm, $T \simeq 2$ µs.

ii) The efficiency

For the single particle the efficiency depends mainly on the purity of the gas. If the oxygen contaminates the chamber, the original electrons are lost by forming negative ions. 1% oxygen in a rare gas of an atmospheric pressure gives the lifetime of electrons to be of the order of 10 µs. This corresponds to 95% efficiency. In the case of 3% oxygen the efficiency decreases to 84%.

If the organic vapour is admixed, the efficiency also decreases because the photons are easily absorbed by the organic vapour and the probability of production of photo-electrons also decreases.

The efficiency depends on the amplitude and the rise time of the pulse. If the low amplitude or the slow rise time of the pulse is used, it is clear that the efficiency decreases.

For the multiple particles the efficiency depends strongly on the characteristics of the pulse. The pulse generator, especially its inner impedance, is essential because the current though the spark is so large that the field intensity across the gap is decreased quickly. Moreover, if the same pulse is applied to the multi-gaps the precise adjustment for equal gap distance is also essential.

iii) Only one spark parallel to the particle trajectory.

The number of original electrons and the quick development of avalanches are essential. The delay between the passage of a particle and the application of the pulse should be shortened. Neon gas gives a good quality of track, because the original number of ion pairs is relatively large and the first Townsend coefficient is also large. The rise time of the pulse should be less than 10 ns and the amplitude of the pulse properly chosen, for instance, 8 ~ 10 kV/cm.

iv) The number of sparks caused by only one particle observed in a chamber applied with relatively low pulse amplitude.

As described in 3 b ii) we can estimate the number of sparks as

$$N = 1 \quad , \quad \text{for} \quad \frac{(d-a)n}{\cos\theta} > 1 \quad \text{and} \quad (d-a)\tan\theta < 2 \text{ mm},$$

$$N = \frac{A}{\cos\theta} \quad , \quad \text{for} \quad (d-a)\tan\theta > 2 \text{ mm},$$

where A is the numerical constant depending on the operational condition and is of the order of 1.

v) The recovery time.

As described in 4) the clearing field does not shorten the recovery time even if a relatively high field is applied, because the space charge in the region of the spark is highly dense and the clearing field cannot interact on the electrons in the space charge. Then the recovery time is fixed by the process of recombination and is of the order of 10^{-3} sec.

TABLE I

The number of ion pairs and δ rays produced by a relativistic particle in rare gases of an atmospheric pressure$^{2)}$.

Gas	No of ion pairs per cm	No of δ rays per cm, (energy > 500 ev).
H_e	8	0.1
N_e	25	0.1
A	40	0.2

TABLE II

The agitation velocity ν_r, the diffusion coefficient D, the drift velocity ν_{drift} and the first Townsend ionization coefficient α of electrons in rare gases of an atmospheric pressure in various electric fields E[9)]

Gas	$E/_p$ volt/cm, mm Hg	ν_r $\mathrm{x10^7 cm/s}$	D $\mathrm{x10^2 cm^2/s}$	ν_{drift} $\mathrm{x10^6 cm/s}$	α ion pairs/cm
H_e	0 (thermal)	1.2	3.1	-	-
	0.2 (150 V/cm)	3.2	7.8	0.4	-
	13 (10 KV/cm)	16	44	15	60
N_e	0 (thermal)	1.2	20	-	-
	0.2 (150 V/cm)	8.8	64	0.5	-
	13 (10 KV/cm)	20	81	14	70
A	0 (thermal)	1.2	3.7	-	-
	0.2 (150 V/cm)	14	18	0.3	-
	13 (10 KV/cm)	20	11	15	10

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Fig. 1 The illustration of streamer formation depending on the spatial separation between two avalanches.
(a) $\ell < 3\rho$. The space charge field intensity between the heads of two avalanches is of the order of the external field intensity. Therefore the additional avalanches are produced in this region and the streamer propagates parallel to the particle trajectory. It is easily understood that when two avalanches are very close the streamer can combine.

In principle at any angle of θ the streamer can propagate parallel to the particle trajectory. However, such a space charge field configuration may not be present when $\theta > 60^{\circ}$ and when an avalanche satisfies the critical condition of Eq. (A) after a long path of development, because the ion clouds may distort such a configuration.
(b) $\ell > 3\rho$. A space charge field intensity between two avalanches cannot become higher, then streamers propagate in the same way as isolated streamers propagate.

When $\ell \sin\theta < 2\rho$, two avalanches transform into one streamer. This condition is applicable to any spatial separation of avalanches.

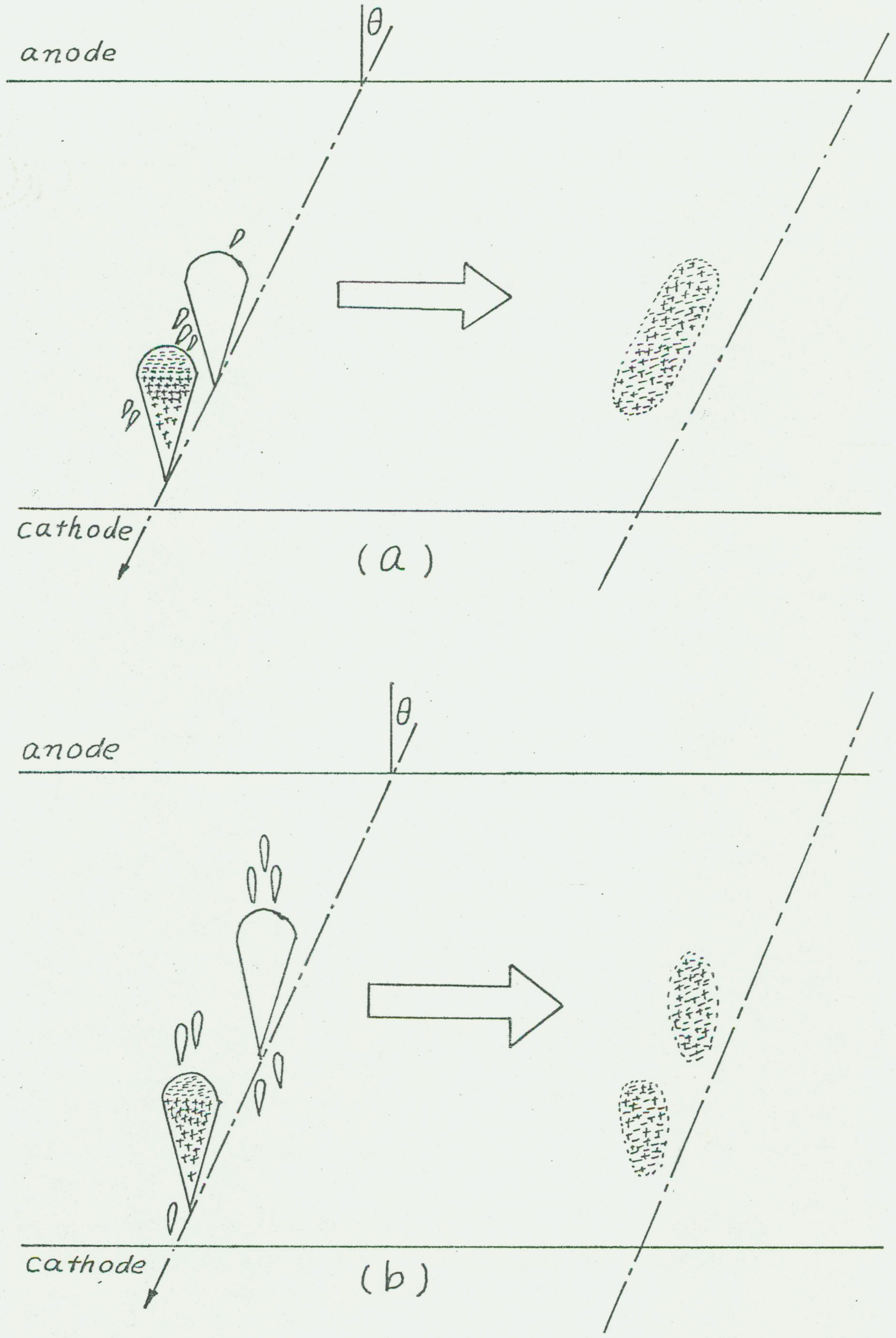

Fig. 1.