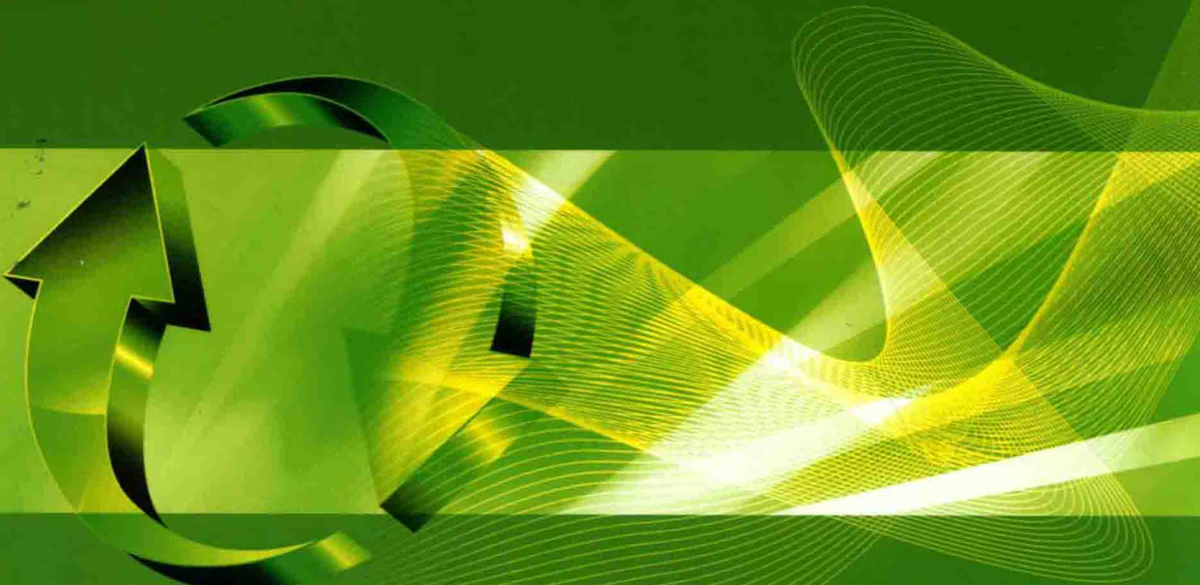
普通高等教育“十二五”规划教材

高电压技术专业英语阅读教程

郑殿春　编著



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内容提要

本书以专业词汇学习和专业知识探索角度为主线条，编撰了包括高电压技术基础知识和反映该领域前沿的专业英语阅读教程，其中包括气、液、固以及复合电介质放电机理，高电压试验技术，高电压设备知识，极端条件下电介质放电现象研究，以及气体放电过程的非线性动力学现象等。

本书可作为高等院校电气工程类高电压技术专业的高年级学生及研究生的专业英语阅读教材，也可供从事电介质放电现象研究的科技人员与高压电气绝缘配合及结构设计的工程技术人员参考。

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前　言

专业英语是建立在公共英语和专业课程基础上的一门工具课，它既是英语学习的继续，也是专业知识学习的延伸，即通过专业英语的学习，掌握本专业或本领域技术信息交流的英语表述方法和规律，可以无障碍地与同行进行学术交流，快速获取本领域技术信息，跟踪本领域发展趋势。所以专业英语课是工科院校培养引领本专业前沿技术人才的手段之一。

随着电力行业的快速发展，我国的超（特）高压输电网络逐渐形成，对高电压技术专业人才的需求极速增加，也为相关高校提供了专业发展契机。本书编著者从事高电压与绝缘技术专业的专业英语教学多年，一直在努力寻找适合本专业教学大纲要求的教材，始终未能如愿。为此，在自己教学实践过程中，通过收集和整理自行编写了《Speciality English for High Voltage Engineering (A&B)》讲义，此讲义基本涵盖了高电压与绝缘技术专业的基本知识体系，并涉及专业英语阅读技巧和写作知识的教学内容，经过多次修正循环使用后构成了本书的基本核心部分，并在此基础上增添了高电压技术领域最新的研究成果内容。

本书的第一章～第四章为基础知识；第五章～第七章为专业知识，不同专业方向可酌情筛选。第八章～第十章涉及此领域的前沿科研方法和成果，可以根据具体情况选读。全书主要内容按照45～60学时编排，其中第一章～第四章可用25～35学时学习，第五章～第七章可用约15学时学习，第八章～第十章作为研究性资料供研究生阅读。

本书的编写出版是一种尝试，目的是使专业英语教学的重点放在专业词汇学习和专业能力培养方面，其中阅读技巧和写作知识应为公共英语的教学环节，不是专业英语的教学内容。第一章～第八章及附录由郑殿春编撰，第九、十章由机械工业仪器仪表综合技术经济研究所郑秋平撰写，全书由哈尔滨理工大学张沛红教授主审。本书的编写出版已经列入“黑龙江省学位与研究生教育教学改革研究项目”，项目编号为：JGXM-HLJ-2014064。

鉴于编著者水平所限，书中难免存在不足与疏漏之处，敬请读者不吝批评指正。感谢电力出版社为本书的出版给予的大力支持。

编　者

2014年10月10日

Contents

Unit 1 Gas Discharge Phenomena

Historically, the term gas discharge refers to the discharge of a plate capacitor through the air gap. Generally, air is a rather good insulator but if the electric field in the gap is high enough, the gas becomes ionized and short-circuits the capacitor gap. Nowadays, any current flow through ionized gas is called 'gas discharge'. The ionized gas is usually luminous, therefore expressions like 'the discharge ignites' or 'burns' are very often in use. Electric discharges can create a low temperature plasma locally. In contrast to high temperature plasmas as in stars or fusion reactors that exist due to heating and magnetic confinement, low temperature plasmas exist under nonequilibrium conditions, etc., due to an externally applied electric field. They generically are inhomogeneous in space and time and form a variety of a spatio-temporal patterns.

Gas discharge (plasma) physics is a wilderness. Nevertheless, we made an attempt to classify discharges using (and introducing) the terminology typical for this field. As a next step of this introductory chapter, we concentrate on a DC driven gas discharge explaining its current-voltage characteristics and different discharge modes. Furthermore, we discuss the mechanism of the Townsend breakdown in general form to illustrate how two ionization mechanisms together can create a stationary discharge. Finally at the end of this chapter, an overview of the microscopic processes responsible for the generation and annihilation of charge carriers is presented. The accent is put only on the processes which we actually use in our modeling of the experiments.

1.1 Classification of Discharges

Gas discharge physics is an interesting and very complex field with a huge amount of experimental data and theoretical models. There is a variety of known discharge types. Among the parameters characterizing the gas discharge are the gas type, its pressure and temperature, spatial dimensions and the shape of the discharge region, presence and composition of electrodes and boundaries, and the kind of energy supply. Internally, a gas discharge is characterized by the electric field and its homogeneity, the ionization rate, energy distribution of particles, spatial distribution of charge carriers, and dominant processes in the plasma. The variety of discharge properties makes a complete and strict classification of gas discharges on the basis of one or two parameters impossible. Though multiple classifications based on specific points of view coexist. First of all, a discharge can be classified according to its temporal characteristics (steady or transient) and dominant processes like space charge effects or heating. The glow discharge glow discharge is an example of a stationary type where space charge effects are essential (while in a Townsend discharge they can be neglected). If heating starts to play a dominant role, the stationary discharge that will develop is an arc and the transient is lightning.

The dominant mechanism of electron reproduction can also characterize the discharge. One can distinguish between either an external ionization source for a non-self-sustaining discharge or gamma and alpha modes for a self-sustaining discharge. On the other hand, the frequency range of the applied fields can serve as a classification:

- DC, low-frequency, and pulsed fields (excluding very short pulses).
- radio-frequency fields (f$\sim 10^5-10^8$Hz).
- microwave fields (f$\sim 10^9-10^{11}$Hz).
- optical fields.

We have seen that the frequency of the externally imposed electric field can be varied over a huge range giving rise to (pulsed) DC, AC, capacitively coupled plasmas (CCP), inductively coupled plasmas (ICP), plasmas induced by micro waves (MIPs) and (laser) light produced plasmas (LIP). Basically all technological plasmas (gas discharges) are created by an electric field which primarily affects the electrons resulting in different charge and currents distributions. By increasing the frequency of the applied electric field the role of the electrodes is reduced since the electrons are basically bounced forward and backward, not having the time to enter a (electrode) wall. In this thesis we focus on a DC situation, thus we are devoted to phenomena where electrodes play an important role. It is always instructive to start with a DC treatment, since space charge-, glow- and arc- like conditions can be found in ICP, MIP etc. as well.

1.2 Current-voltage Characteristics of DC Discharge

DC discharges are commonly classified on the basis of the current-voltage characteristic of the gas discharge of which a typical example is given in Fig. 1-2. The presented situation corresponds to a discharge in a long tube at relatively low values of the pressure. The tube can be filled with various gases. Two metal electrodes are inserted at the ends of the tube and connected to DC power supply via a series resistor as can be seen in Fig. 1-1. This is classical experimental setup which serves well to study many different types of discharges.

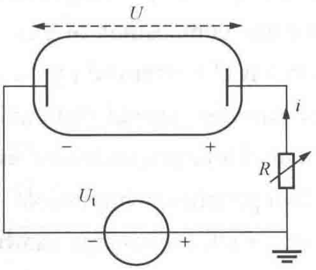

Fig. 1-1 Classical experimental setup for the investigation of different modes of a DC discharge

The steady state of the discharge is defined as the crossing point of the current-voltage characteristics and the load line of the external circuit, which consist of a power supply and a resistor in series. Depending on the applied voltage U_t and the resistance R, the load line can intersect the current-voltage characteristic in different regimes therefore defining which mode of the discharge will develop. In this thesis, we will operate in the regime of Townsend to glow discharge and corresponding current-voltage characteristics can have different shape than the one presented here in Fig. 1-2.

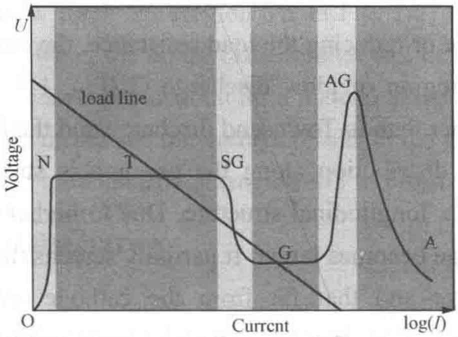

Fig.1-2 A semi-log plot of a gas discharge current-voltage characteristics

Different discharge modes are marked with gray vertical bands and denoted with abbreviations: N for Non-self-sustaining discharge; T for Townsend discharge; SG, G, and AG for subnormal glow discharge, glow discharge, and abnormal glow discharge, respectively; A for arc discharge. Load line defines the operating mode studied in this thesis.

1.2.1 Non-self-sustaining Discharge

If the applied voltage is below the breakdown threshold, no visible effects are produced though a very small current can be measured. The gas is practically an insulator and current is carried by charged particles which are always present due to cosmic rays or other ionizing agents (like the natural radioactivity). This discharge is not self-sustaining which means that it would extinguish if all ionizing agents were removed. Non-self-sustaining discharge corresponds to the region at the very beginning, of extremely steep voltage growth in the current range denoted as N in Fig. 1-2. One can see that the current density saturates quickly while the voltage increases. Saturation corresponds to the situation where all electrons and ions generated in the gas volume are collected by the electrodes, therefore the current is limited by the rate of ionization.

1.2.2 Townsend Discharge

With further increase of the voltage, after the threshold of simple charge reproduction (1.2) is reached, stationary state of gas discharge is broken and the current grows exponentially several orders of magnitude at nearly constant voltage. The limiting factor for this growth is the resistance of the external circuit. If the external impedance is high enough, the load line of the external circuit crosses the current-voltage characteristics in region T (Fig. 1-2). This discharge regime is known as the Townsend discharge. Avalanches develop in the entire volume of the gas and leave behind traces with positive ions which drift slowly due to a low mobility, towards the cathode. Electrons have a high mobility and move very fast to the anode. Thus, non-compensated positive space charge is formed in the gas volume. However, the current in Townsend discharge is so small that the space charge is negligible and does not distort the electric field in the gap. The Townsend discharge, also called dark discharge, is characterized by a weak luminosity and a low ionization rate of the gas.

1.2.3 Glow Discharge

Increasing the external voltage or reducing the load resistance, the current increase and the crossing point can be located in the region of glow discharge G (Fig. 1-2). The charge density in glow discharge is substantially higher than in Townsend discharge and the field of space charge cannot be neglected. The electric field distribution along the gas gap is strongly inhomogeneous and the discharge may have a complex longitudinal structure. Due to higher current than in the Townsend mode, the positive space charge becomes larger. It partially screens the cathode so that the field near the cathode becomes stronger and that far from the cathode weaker than in the case of a homogeneous breakdown field. The drop of avalanche amplification in the rest of the gas gap behind the cathode region is easily compensated by amplification growth in the cathode region of the strong field. In the steady state, the field is concentrated near the cathode and avalanches develop there. In the rest of the gap between the electrodes the field is very weak and practically no ionization occurs. The electrons born in avalanches near the cathode drift slowly through this region gradually gaining energy from the field and exciting the neutral particles of gas. Due to the glow of excited atoms, the discharge is referred to as a 'glow discharge'. The existence of the cathode layer with a strong field, where the charge multiplication and reproduction, necessary for self-sustaining discharge occurs, is the essential attribute of a glow discharge.

The region of constant weak electric field is referred to as the positive column. There, electrons with a low mean energy are drifting slowly to the anode. However, some of them have a high energy and they are responsible for the ionization in the column, which compensates the electron losses. Weak luminosity of the positive column is produced by a small amount of these highly energetic electrons, which are present in the electron energy spectrum. Sometimes, the emitted light is not homogeneous, but has a periodic layered structure composed of striations. The positive column may have a different length and becomes shorter or disappears completely if the electrodes are shifted towards each other.

The efficiency of ionization depends strongly on the electric field. The field concentration near the cathode can make the ionization so effective that the total voltage (including the voltage drop on the positive column) required for a self-sustaining glow discharge can be lower than that for Townsend discharge with a homogeneous field and ionization in the entire gas volume. This explains the falling of the current-voltage characteristic by the transition from Townsend to the glow discharge (Fig. 1-2). However, in some other range of parameters (much smaller pd for instance), transition from Townsend to glow discharge has monotonically increasing current-voltage characteristics.

The current range of glow discharge can be orders of magnitude wide, whereas the required voltage remains nearly constant. The remarkable property of glow discharge to keep a so-called 'normal' current density is responsible for this adaptivity. As the discharge current varies, the normal current density at the cathode is preserved and the occupied area at the cathode is changed. If the current is decreased (for instance, by an increased ohmic load in series with gas), the current spot at the cathode contracts until its size becomes comparable with the thickness of the cathode layer. The electron losses from the current channel become larger, and a higher voltage is necessary to support the discharge: the subnormal glow discharge (region SG in Fig. 1-2) takes place. If the current of a normal glow discharge keeps growing, the entire cathode area will be covered with the discharge of the normal current density. This is a 3D explanation for a plateau in the normal glow discharge region. Further increase of the current by increasing the voltage results in the growing of the current density. This is the transition to abnormal glow discharge (region AG in Fig. 1-2).

1.2.4 Transition to Arc Discharge

In the abnormal glow discharge, the required voltage grows rapidly with the current density, and becomes high enough to produce substantial heating of the cathode. The thermal ionic emission from the cathode grows, resulting in more electron avalanches. This leads to a higher density of charge carriers, i.e., to lower resistance, and, consequently to higher currents. When the current reaches approximately a value of 1 A glow discharge cascades down to an arc discharge The current-voltage characteristics falls (see the region A in Fig. 1-1) and the arc needs only tens of volts for support. The arc releases large thermal power and can destroy the glass tube.

Since this thesis focus on the transition from Townsend to glow discharge, the arc discharge is not discussed further.

1.3 Townsend Breakdown

The primary element of the often very complicated breakdown process is the electron avalanche, which develops in gas when an electric field of sufficient strength is applied. An avalanche begins with a small number of seed electrons that appear accidentally, e.g., due to cosmic rays. An electron picks up energy in the electric field. Having reached an energy higher than the ionization potential, the electron ionizes an atom or a molecule, thereby losing its energy. The two slow electrons resulting from this process are in turn accelerated in the field and ionize two atoms or molecules. Thus, an exponential growth of the number of electrons and ions takes place. The breakdown is essentially a threshold process. It occurs only when the field exceeds a certain critical value. By a gradual increase of the field under the threshold value, no noticeable changes in the state of the gas can be observed. By reaching the breakdown field, ionization rises dramatically, a current through the gas can be detected, and a light emission can be seen. Such a behavior is a consequence of the steep dependence of the rate of atomic ionization by electron impact on the field strength. But, on the other side, avalanche is slowed down by electron energy losses and by the loss of electrons themselves. Electrons lose energy to excite electron states of atoms and molecules, and molecular vibration and rotation. Electrons also lose energy in the electric field if they move against the drift direction after elastic collisions. These will lead to an obstruction of the accumulation of electron energy. Diffusion leads to the removal of electrons from the field (e.g., precipitation on the walls), attachment in electronegative gases leads to direct electron losses, and the drift of electrons to the anode also removes them from the discharge. Because of the low electron density, the recombination rate at this stage is low as well, and practically does not contribute in the removal of electrons. The electron losses are breaking chains in the multiplication chain reaction. The breakdown threshold is determined by the relation between creation and removal of electrons. The electronic current at the anode can be calculated as an exponentially amplified electronic current at the cathode

$$i_{1a} = i_{0c} e^{\alpha d} \tag{1-1}$$

where: α is Townsend's ionization coefficient, d is the distance between electrodes and $\boldsymbol{i_{0c}}$ is the electron current at the cathode.

The first Townsend coefficient α describes the multiplication rate and represents the number of ionization events performed by an electron in a 1 cm path along the field. It can be defined as a function of the reduced field (E/N) or, in the case of a constant temperature, (E/p), where E is the electric field, N is the concentration of neutral gas particles, and p is the pressure. Strictly speaking, the first Townsend coefficient depends on the mean energy of the electrons, and not on the electric field. However, for a field with small gradients, i.e., for a field which can be considered as constant on the mean ionization length of electrons, the assumption $\alpha = f(E/N)$ is valid.

Electron avalanche leaves behind positive ions, which drift slowly to the cathode. The ion current at the cathode includes all ions generated in the avalanche

$$i_c = i_{1a} - i_{0c} = i_{0c}(e^{\alpha d} - 1) \tag{1-2}$$

This is the primary process in the volume of the discharge. The secondary process is the generation of secondary electrons at the cathode with the help of the particles generated in the primary gas ionization process. Especially important is the generation of secondary electrons by ion bombardment of the cathode.

The ratio of the emitted electrons and impacting ions is called γ—the secondary emission coefficient.

The secondary electrons are then multiplied in the gas gap and the electron current at the anode is

$$i_{2a} = \gamma i_c e^{\alpha d} = \gamma(e^{\alpha d} - 1) \cdot i_{0c} e^{\alpha d} \tag{1-3}$$

Each electron avalanche is amplified by the factor

$$b = \frac{i_{2a}}{i_{1a}} = \gamma(e^{\alpha d} - 1) \tag{1-4}$$

The stationary current is then determined by the limit of geometric progression

$$i = \frac{i_{0c} e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \tag{1-5}$$

An equation of this type was first derived by Townsend in 1902. For a non-self sustaining current, the denominator in Equation (1-5) is positive and less than one.

With a voltage increase, α grows until the denominator in Equation (1-5) becomes equal to zero and then negative. The current cannot be stationary at this point and the formula becomes meaningless.

In the case of $\gamma(e^{\alpha d}-1) > 1$, the number of secondary electrons is larger than that of primary electrons. The exponential growth of their number is then guaranteed. The external source of electrons is no longer necessary and the discharge becomes self-sustaining. The condition for initiating a self-sustaining discharge describes the simple reproduction of electrons.

$$\gamma(e^{\alpha d} - 1) = 1$$

or

$$\alpha d = \ln(1/\gamma + 1) \tag{1-6}$$

The transition of non-self sustaining to self-sustaining discharge can be interpreted as the onset of breakdown. The threshold voltage U_b, which corresponds to the condition of a steady self-sustained current in the homogeneous field

$$E_b = U_b / d \tag{1-7}$$

is considered as the breakdown voltage. Breakdown voltage U_b (and corresponding breakdown field E_b) depends on the gas type, the pressure, the width of the discharge gap and the material of the cathode. Explicit expressions are

$$U_b = \frac{B(pd)}{C + \ln pd} \qquad \frac{E_b}{p} = \frac{B}{C + \ln pd} \qquad C = \ln \frac{A}{\ln(1/\gamma + 1)} \tag{1-8}$$

derived by inserting the Townsend approximation $\alpha(E) = Ap\exp(-Bp/|E|)$ into the ignition equation (1-2). The breakdown voltage, calculated in that way, with an experimentally determined constants A and B, usually gives a satisfactory agreement with the experiment.

Experimental curves expressing the dependence of the breakdown voltage on discharge system parameters as gas pressure and the distance between the electrodes, are called Paschen curves. The curves have a clear minimum which means that a minimal breakdown voltage for the discharge gap exists.

According to Equation (1-8), the parameters of this minimum point are

$$(pd)_{\min} = \frac{\bar{e}}{A} \ln(1/\gamma + 1) \left(\frac{E}{p}\right)_{\min} = B, \quad (U)_{\min} = \frac{\bar{e}B}{A} \ln(1/\gamma + 1) \tag{1-9}$$

where: $\bar{e} = 2.72$ is the base of Natural logarithm. These expressions together with the experimental Paschen curves, can be used for the estimation of the secondary emission coefficient, since only the value of $(E/p)_{\min}$ does not depend on the cathode material. That value corresponds to the point (Stoletov's) where ionization capabilities of electrons are at a maximum.

At the left-hand branch and right-hand branch of the Paschen curve different physics is taking place. At the left-hand side, the steep increase of the breakdown voltage towards lower pd values corresponds to the transition to vacuum breakdown. Electrons there experience fewer collisions on their way to the anode and the ionization efficiency α has to be very high, i.e., a high electric field is necessary to maintain the process. To the right of the minimum, the breakdown voltage grows as well. In this case electrons have many collisions but their ionization efficiency is low due to either a lower electric field (if the distance between electrodes d becomes larger) or a shorter mean free path (if the gas pressure p becomes higher). This similarity law is valid for a rather broad range of pressure and distance between the electrodes.

Strictly speaking, the voltage necessary for the breakdown should be slightly higher than U_b in order to ensure the expanded reproduction of electrons. The current and ionization in the gas will then increase until the growth is stopped by recombination or the ohmic resistance of the circuit. As the current increases, the resistance accepts a progressively greater part of the supply voltage, the voltage on the electrodes decreases until it reaches U_b and the current becomes stationary. The characteristic retardation time of the breakdown is on the order of 10^{-5} to 10^{-3}s. It consists of the statistical time of waiting for a seed electron and of the breakdown development time, which depends on both the electron multiplication rate and the characteristic time between two consequent generations of secondary electrons.

Multiple avalanches may develop simultaneously and each avalanche spreads transversally. due to electron diffusion, so that new avalanches can start at different spots of the cathode. As a result, the Townsend breakdown most often involves the entire volume of the gap in a diffuse manner. This is the clear difference from the other breakdown mechanisms.

1.4 Production and Loss of Charges in a Gas

There are two different categories of elementary discharge processes, namely volume processes and wall processes. To the volume processes where new charge carriers are generated, belong direct electron impact ionization, photoionization, Penning ionization (important in a gas mixture) and *associative* ionization (important in the inert gases). Volume processes where the number of free electrons decrease are attachment and recombination. The excitation process also belongs to volume processes but it does not change the number of charged particles directly, but slows down the electrons. An excitation process occurs if the electron energy is big enough to bring the atom into an excited state. The excited atom may later participate in ionization processes or undergo a transition to the ground state with emission of a photon which is usually the reason of discharge glow.

In the atomic gases, the most important volume process is the ionization by electron impact. In the simplest case, it occurs if the electron has obtained from an electric field more energy than necessary to ionize the neutral atom and can be described by the formula

$$A + e^- \rightarrow A^+ + 2e^-$$

Attachment of an electron to a neutral atom or molecule leads to a generation of negative ions. This process plays an important role in electronegative gases, such as O_2, Cl_2, and SF_6. It decreases the concentration of electrons and thus influences the development of avalanches. Negative ions have very low mobility and practically do not take part in excitation or ionization processes. This leads macroscopically to a higher breakdown field, therefore these gases are often used as insulators. Discharge is very sensitive to this process and even a small amount of oxygen or water vapor in the discharge gap leads to a strong increase of the breakdown voltage.

The most important wall processes are the removal of charge carriers from the gas volume and the generation of secondary charge carriers.

For the generation of secondary charge carriers, electron emission from wall (electrode) surfaces is important and there is a large variety of electron emission mechanisms which will not be discussed. Secondary electrons can also be emitted under the influence of various particles: Positive ions, excited atoms, electrons, and photons. Secondary emission from a cold cathode produces breakdown of the discharge gap and also sustain a small DC current that is incapable of substantial heating of the cathode or of creating such a strong field at the cathode that thermionic or field emission develops. The most important secondary emission process is the ion-electron emission. It is characterized by the second Townsend coefficient γ_i. The number of secondary electrons emitted per incident positive ion. The kinetic energy of ions is practically the same as that of neutral particles (on the order of 10^{-3} eV) and is insufficient to knock out an electron. The energy necessary for an electron to escape is obtained by the neutralization of the ion. The electric field of an ion on a distance comparable to atomic dimensions is very strong and transforms the potential well on the surface into a low and very narrow potential barrier. An electron from the body (metal, semiconductor or dielectric) tunnels to the ion and neutralizes it. The released recombination energy may be then spent on the emission of a second electron.

Expressions and Notes

[1] homogeneity: *n.* 同种，同质，同次性

[2] though: *conj.* 虽然，尽管；即使；纵然；
adv. 可是，但是；不过；然而；话虽这样说；
prep. 但

[3] glow discharge: 辉光放电

[4] technological: *adj.* 技术上的，工艺（学）的，因技术革新而造成的

[5] are devoted to: 专心于…

[6] instructive: *adj.* 有益的，教育性的

[7] setup: *n.* 机构，设置，装备，组织，计划，调整