Chapter 1
Introduction

According to the definition, gas discharge is the passing of an electric current through a gas. Correspondingly, a gas discharge plasma is a matter that provides this process. It is a weakly ionized gas that is supported by an external electric field. A gas discharge plasma as a physical object is an nonequilibrium system because of the character of energy transmission from an electric field to a gas through electrons. Indeed, electrons as more mobile charged atomic particles acquire an energy from the electric field and then transfer it to gas atoms or molecules in collisions with them. From this it follows that the kinetic theory is necessary for description a gas discharge plasma, and the velocity or energy electron distribution function (EEDF) is one of characteristics of a gas discharge plasma under consideration.

The first self-consistent scheme of a gas discharge plasma was represented by Townsend [42] and has the form

$$e + A \to 2e + A^+, \; A^+ + M \to A + M^+ + e \qquad (1.0.1)$$

Within the framework of this scheme the ionization equilibrium is established as a result of collisions of electrons (e) and atoms (A), and electrons are reproduced in collisions of ions (A^+) with the cathode surface (M). Such collisions lead to formation of secondary electrons. This scheme is working under certain conditions and is described by two parameters, namely, by α, the first Townsend coefficient, and by γ, the second Townsend coefficient (we exclude from the Townsend scheme ion-atom collisions). Here $1/\alpha$ is the mean free path of electrons in an external field with respect to atom ionization, and γ is the probability of formation of a secondary electron at the cathode as a result of collision with the cathode surface for an ion which is accelerated by an electric field. This scheme allowed one to explain the principal properties of gas discharge on the first stage of its study [1–5]. In addition, this understanding of physics of gas discharge gave an impetus for measurements the parameters of various processes involving electrons in gases located in an electric field [6, 7, 12, 43], such as the drift velocity of electrons, the transverse and longi-

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tudinal diffusion coefficients of electrons, the effective electron temperature that is the ratio of the transverse diffusion coefficient to its mobility, the first and second Townsend coefficients and rates of various processes.

The principal property of a gas discharge plasma is its self-consistency. A space self-consistency of a gas discharge plasma follows from the Townsend scheme and leads to a nonuniform space distribution of a gas discharge plasma. If this plasma is located in a cylinder tube, this leads to separation of gas discharge in the cathode layer where electrons are generated, and the positive column with a low electric field strength, so that this plasma distribution provides the minimum voltage between electrodes. A kinetic self-consistency of a gas discharge plasma means that processes of atom excitation and ionization by electron impact lead to a drop of the electron distribution function above the thresholds of corresponding processes that in turn influences on the rates of these processes [44, 45]. Along with a self-consistency of a gas discharge plasma, its complexity may be connected with various schemes of the ionization equilibrium in a plasma if it is determined by different processes. As a result, many regimes and types of gas discharges may be realized each of these is supported by certain processes (for example [18]). Hence, various regimes of a gas discharge plasma may exist depending on used gases or gas mixtures, their pressures, electric currents and powers of gas discharge, temporary dependence for used fields and on the geometry of a gas discharge system. Due to the variety of these parameters, a gas discharge plasma cannot be described within an universal scheme of the ionization balance and basic processes as it takes place in the Townsend case. In addition, because of the complexity of this object, the description has usually a qualitative character and is based on simple models. In particular, tau-approximation for the kinetic equation of electrons is used, as well as simplified parameters of basic processes. Though this description does not allow one to obtain numerical parameters of a certain gas discharge plasma under given conditions, but only on the basis of this approach one can analyze many various discharge types simultaneously.

Hence different types of a gas discharge plasma as a physical object are not described within the framework of an universal scheme, and a family of gas discharge plasmas is analogous to a mosaic, where each type requires a specific scheme and used parameters. One can expect the contemporary development of the gas discharge plasma theory must be based on computer simulation that must be addressed to a certain gas discharge plasma and conditions which accompany this plasma.

The interest to a gas discharge plasma is connected with its various applications. In turn, development of applications induced a more deep study of a gas discharge plasma. Moreover, experimental investigation of gas discharge in a gas filled tube as a light source allowed one to formulate for Langmuir [46, 47] a plasma as a physical object. He exhibits that a matter inside a tube is a uniform quasineutral gas that includes electrons and ions. According to Langmuir [46] "we shall use the name plasma to describe this region containing balanced charges of ions and electrons". The plasma sheath is formed near electrodes and according to the Langmuir analysis of the positive column of mercury arc in 1923 [48] "Electrons are repelled from the negative electrode while positive ions are drawn towards it. Around each negative electrode there is thus a sheath of definite thickness containing only positive ions and neutral atoms".

The first application of a gas discharge plasma, gas discharge lamps, was started more than a century ago. These lamps were gas discharge tubes filled with an inert gas and mercury addition. The light color was determined by an inert gas type. From that time an efficacy of gas discharge lamps was increased up to 100 lm/W (the efficacy of an incandescent lamp is approximately 14 lm/W), as well as a number of their types. Along with inert gases with a mercury addition, gas discharge tubes may be filled with sodium, sulfur, hydrogen, deuterium, nitrogen, oxygen and halogens. In addition, various metal vapor additions may be used in gas discharge tube filled with inert gases. An example of a contemporary lamp of white color is represented in Fig. 1.1.

A subsequent development of technics of gas discharge lamps is connected with gas lasers as a source of coherent radiation. He-Ne and argon lasers are the most spread laser types. Recently, lasers in a vacuum ultrahigh radiation and X-ray lasers on transitions between ion levels were created on the basis of capillary discharge. This discharge provides high electron energies that allows one to generate short-wavelength radiation. As an example, Fig. 1.2 gives a scheme of transitions for Ne-like argon multicharge ions which allows one to generate laser radiation at the wavelength 46.9 nm [50–52].

Gas discharge is a simple method to create a plasma, and because gas discharge has many regimes and forms which are increased in time, a number of applications of a gas discharge plasma grows. Often new applications are based on old ideas, as

Fig. 1.1 Fluorescent lamp as a source of visible light [49]

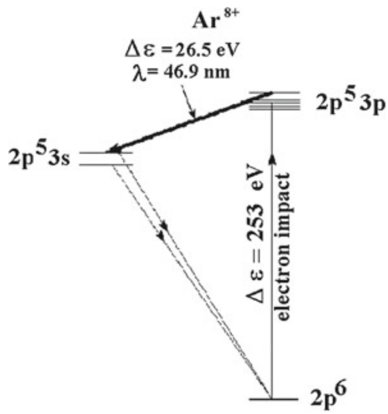

Fig. 1.2 Scheme of transitions in X-ray laser based on transitions between Ne-like levels of a multicharge argon ion in capillary gas discharge [50–52]

plasma displays. Its concept for television was described in 1936 by Tihanyi [53] as a system of single transmission points of a grid with cells arranged in a thin panel display, where these points are excited to different levels by varying the voltages at this point. But production of plasma displays started in eighties when they can compete with electron-beam tubes or liquid crystal displays. Roughly, the plasma display construction includes two parallel planes with parallel bus-bars in each plane. Bus-bars of each plane are surrounded by dielectric planes and bus-bars of different planes have perpendicular directions. As a result, the space inside the bas-bar plane is divided in some cells, and each cell relates to one intersection of bus-bars. The space is filled with a mixture of nitrogen and neon (or other inert gas), and gas discharges occur in each cell almost independently. In back to the cathode each cell is divided in three parts covered by colored luminophors, so that after absorption radiation of local gas discharge one of subcells gives a red color, second one gives a green color, and the third subcell transforms radiation of gas discharge in a blue color. These three colors are joined in the overall color of this element that depends on the intensity of local discharge, and this intensity in turn is operated through bus-bars. Competing with other types of displays, plasma displays or plasma panels are favorable for screens of large sizes and their applications are determined by possibilities of a new technology [54–57]. A subsequent development of the plasma panel technics allows one to use this system as a detector of radiation [58] and even for muon detection [59].

Another system where a plasma is used for generation of electric energy is the thermoemission converter. It contains two parallel metal plates with different work functions (the work function is the binding energy of an electron at a surface). One of these plates is heated and emits electrons which reach the other plate, i.e. an electric current occurs between electrodes. Connection of the plates through a load leads to release of the electrical energy in the load. It is evident that a plasma is not the underlying basis for this device. Nevertheless, using a plasma in the gap between the plates, one can overcome this trouble. If a plasma is absent in the gap, electric charge occurs in this region that creates a blocking voltage and locks a current. For typical energy fluxes in these systems $\sim$1W/cm^2 the distance between plates must be less than 10 μm. It is difficult to combine a high temperature of the heated plate $\sim$2,000 K with small gap sizes, and a gap plasma allows one to overcome this trouble.

In various applications of a plasma with an intense input of energy, the plasma is generated in a moving medium. The plasma generator or plasmatrone is usually arc discharge in a flowing gas or vapor that produces an equilibrium thermal plasma [36]. As a result, plasma torches are formed with wide applications in various technological problems including incineration of waste and special medical uses. A moving gas discharge plasma is used in rocket-propelled vehicles [60–64]. Indeed, the velocity of combustion products of a rocket vehicle with a chemical fuel is of the order of the sound speed, or of the order of 10^6 cm/s. In reality one can accelerate ions in an electric field up to 10^8 cm/s, but ion currents are small because a space charge locks the ion current. To increase this current, one can use a gas discharge plasma which is accelerated in various configurations of electric and magnetic fields. Of course, the power of such engines is some orders of magnitude lower than that for engines with a chemical fuel, and hence such rocket-propelled vehicles may be used for the control of a spacecraft motion in a space.

Many plasma applications are based on the possibility to insert a high electrical energy in the plasma. This leads to the creation and maintenance of an ionized gas containing active atomic particles, electrons, ions, excited atoms, radicals. These particles may be analyzed by a variety of techniques, and therefore a plasma can used not only in energetic systems, but also in measuring instruments. In particular, plasma-based methods of spectral analysis are widely used in metallurgy. In these methods a small amount of metal in the form of a solution or powder is injected in a flowing arc plasma, and spectral analysis of the plasma makes it possible to determine the metal composition. The accuracy of this spectral determination of admixture concentration with respect to a primary component is of the order of 0.01–0.001 %. The optohalvanic method [65, 39] that is based on the connection between radiative and ionization properties of a gas discharge plasma allows one to detect small concentrations of gas and vapor admixtures up to 10^{-10}–10^{-9} g/g. In such an analysis gas discharge is burnt, and a laser signal is tuned to a resonant line of a given element that leads to variation of a gas discharge current due to subsequent ionization processes.

Plasma processing for environmental applications is developing in two directions. The first one is decomposition of toxic substances, explosive materials, and other hazardous wastes which are injected in an arc plasma and are decomposed in a plasma into simple chemical constituents. The second one is connected with an improvement of air quality by using corona discharge of a low power. This discharge generates active atomic particles, such as oxygen atoms. These atoms have an affinity for active chemical compounds in air and react with them. Such discharges also destroy microbes, but do not lead to hazards for humans because of low concentrations of these particles.

Plasma applications are widen in time and are included in new sides of the man activity. Plasma applications in medicine started several decades ago and are based on the mechanical or chemical action of a plasma on a living object. For example,

Fig. 1.3 Plasma knife (or plasma scalpel) for surgery [66]

a plasma knife that is a think plasma flux is used similar to a knife in surgery. An example of this instrument is represented in Fig. 1.3. As a matter, it is a flowing plasma which propagates through a nozzle or orifice in atmospheric or rareness air. Depending on tasks, different types of a gas discharge plasma may be used, and specific requirements relate to the wall material that must not be destroyed under the action of this plasma during a long time. In a simple construction, the basis of a plasma knife may be capillary discharge where plasma motion outside results from electron drift in an electric field.

The action of a plasma as an active media may be various because of existence of many plasma forms. In particular, destruction of medical waste including bandages, medicinal cotton and other disposable materials, with using an arc plasma proceeds similar to combustion of these materials in oven, but plasma set up is more compact and exclude danger products, though it is also more expensive. Nevertheless, plasma methods are more favorable in practice than combustion of medicine materials in oven. A not so power plasma intends for decontamination and sterilization of medicine tool. Because a plasma contains various active particles, as electrons, ions, metastable atoms and molecules, radicals, it is applied in wound healing, dermatology and dentistry where the plasma kills microbes and does not destroy a living tissue. Of course, a suitable plasma form and a certain current regime must be used for each case and follows from the corresponding study. In addition, plasma technology is used for production of specific medicine materials and devices.

The oldest applications of a plasma as a heat-transfer agent [36, 67] are in the welding or cutting of metals. Since the maximum temperature in chemical torches is about 3,000 K, they cannot be used for some materials. The arc discharge (electric arc) allows one to increase this temperature by a factor of three compared to chemical sources of energy, so that melting or evaporation of any material is possible by plasma methods. Therefore the electric discharge is used starting a century ago for welding and cutting of metals. Presently, plasma torches with power up to 10 MW are used for iron melting in cupolas, for scarp melting, for production of steel alloys, and for steel reheating in tundishes and landlies. Plasma processing is used for extraction of metals from ores. In some cases plasma methods compete with traditional ones which are based on chemical heating. One can conclude from comparison plasma and chemical methods that plasma methods provide a higher specific output, a higher quality of product, a smaller amount of waste, but require a larger energy expenditure and more expensive equipment. In particular, this relates to plasma chemistry [68–73] that allows one to produce various chemical compounds and some of them may be obtained on the basis of standard chemical methods. Especially plasmachemical processing is convenient for production fine chemical compounds including both inorganic materials and organic compounds. The latter includes the production of polymers and polymeric membranes, processes of fine organic synthesis in a cold plasma [70, 71, 74], etc. In a qualitative assessment of the technological applications of plasmas, we conclude that plasma technologies have a sound basis, and present promising prospects for important further improvements.

Returning to the theory of a gas discharge plasma, we note a lot of geometric constructions of gas discharges and configurations of electric and magnetic fields. Various gaseous components, different parameters of these components and external fields create various regimes of evolution of such a plasma and a variety of processes which determine the plasma properties and its evolution. In other words, if at a given construction of gas discharge such parameters as its power, the current strength, the pressure of a gas (and especially, its composition) vary, a lot of regimes of gas discharge is realized, and these regimes are determined by different processes in a gas discharge plasma. Therefore, though general principles of gas discharge are understood a century ago, new types of gas discharge for certain applications are created now. For this reason a universal description of a gas discharge plasma is cumbrous and is not practical. Being guided by certain plasma components and field configurations, one can restrict a group of process that is responsible for plasma properties and the character of its evolution. In this book we restrict ourselves by helium and argon as plasma components, by the cylinder and plane geometries of a gas discharge chamber, and also by constant electric and magnetic fields. Thus, the goal of this book is the modeling of a gas discharge plasma of helium and argon at a simple field configuration.

Let us formulate a general scheme for the model of a gas discharge plasma. Because of a non-equilibrium character of kinetics for electrons and ions in a gas discharge plasma [41, 75, 76], the model of a gas discharge plasma must be based on the concept of the distribution function of electrons and ions. In other words, hydrodynamic and thermodynamic description of a gas discharge plasma has a qualitative character. In addition, it is necessary to take into account a real dependence of the cross sections on the collision energy, in particular, the Ramsauer effect in the cross section of elastic electron-atom scattering. In this case the minimal cross section is two orders of magnitude less than the cross section at zero electron energy. It is clear that the tau-approximation that is used often in the analysis of kinetics of a gas discharge plasma and simplifies this analysis, is not applicable in this and other case. From this it follows that detailed information about the dominant processes is required for the kinetic analysis of a gas discharge plasma, and this information is analyzed in this book for processes in a helium and argon plasma.

Thus, violation the equilibrium in the gas discharge plasma under consideration is of importance. In particular, an electron energy changes weakly in single collisions with atoms and ions because of a large mass difference. Hence, an average electron energy is enough to ionize gas atoms at moderate electric field strengths, while an average ion energy is close to a thermal energy of gas atoms. Another example relates to propagation of a plasma in a gas on its boundary, in particular, near the walls of a chamber where this plasma is located. Then the rate of plasma motion is determined by electrons as a light plasma component, and along with diffusion of these electrons in a gas their displacement is determined by ion drift under the action of an electric field that is created by electrons which move away from ions and pull them. If the electron average energy exceeds the ion energy significantly, this field gives the main contribution to the rate of plasma propagation to its boundary. These examples exhibit the specifics of a gas discharge plasma as a non-equilibrium object.

Evidently, methods of computer simulation may be used for the analysis of a certain gas discharge plasma. In contrast to an universal analysis which has a descriptive character like to [18], computer simulation allows one in principle to describe a certain gas discharge plasma. For example, computer simulation of an argon gas discharge plasma is fulfilled in [77–81] with taking into account a large number of excited states. In particular, in the Vlacek model [82] that is the basis of evaluations [78–80] in which 64 levels are included. But in spite of the affinity of these evaluations, they are not reliable, i.e. their results do not correspond to real objects. Indeed, the authors are focused on computer aspects of the problem and cannot consider correctly peculiarity of processes which accompany a certain problem. We give one of reasons of the result invalidation. The atom excitation process by electron impact in a gas discharge plasma is the consistent process [44, 45, 83], i.e. the electron distribution function above the excitation threshold decreases sharply with an increasing electron energy, and this in turn influences on the process rate. This fact is not taken into account in the above papers [77–81]. These troubles are determined by the complexity of the problem where a certain nonuniform gas discharge plasma is an object of each paper. This means that though just computer simulation is the prospective method for the analysis of a nonuniform gas discharge plasma, the contemporary computer analysis of a certain gas discharge plasma is not reliable because of ignoring the peculiarities of processes in this plasma in this analysis.

We keep another position compared to computer specialists who use universal computer codes without a careful analysis of the processes and kinetics of gas discharge plasma. It is convenient to divide a general problem in some blocks, and each block solves a certain problem. In particular, in the cases of a helium and argon gas discharge plasma under consideration the first block includes the kinetics of a uniform gas discharge plasma with elastic and inelastic processes electron-atom collisions, electron-electron collisions and radiative processes. The second block relates to a nonuniform plasma and considers the kinetics, transport phenomena in this plasma and its ionization balance. Note that the first block may be identical for different problems of a gas discharge plasma if the same processes are its basis. This approach requires simple computer codes, but allows one to obtain reliable results. We also tend the accuracy of this approach to be in accordance with the accuracy of information used.

Practically, this book demonstrates the indicated approach based on the analysis of physics of a gas discharge plasma. Moreover, the most part of the book is devoted to the analysis of processes, kinetics and properties of a uniform gas discharge plasma, rather than computer simulation of problems of nonuniform gas discharge plasmas. This exhibits that the understanding of the problem and its details with treatment of information is of importance for solution of a certain problem. Moreover, computer codes may be simplified significantly compared to universal computer codes if the physics of a certain problem is clear. On contrary, replacing of the problem understanding by universal and complex computer codes makes the result to be unreliable.

This book consists of four parts, so that first three parts contain a description of processes in a gas discharge plasma and the analysis of properties of simple gas discharges. The fourth chapter is devoted to various aspects of gas discharge plasmas of helium an argon. General properties of a gas discharge plasma and processes in this plasma, mainly elementary ones, are analyzed in the first book part. Kinetics of a gas discharge plasma and transport phenomena in this plasma are the content of the second book part. The third part of the book is a description of elements of simple gas discharges. The four part is devoted to a uniform helium and argon plasma, and properties of such a plasma in the positive column, in the cathode layer and near the walls of a gas discharge chamber is considered in the fifth part of the book. Believing that properties of certain gas discharge plasmas and processes which are responsible for regimes of this plasma and its evolution, we give in a preface a list of books where physics of some gas discharges is analyzed.

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