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The Contribution of Nikola Tesla to Plasma Physics and Current Status of Plasmas that He Studied

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Abstract: One of the main Interests in science of Nikola Tesla were gas discharges, plasmas, their application in lighting and in production of ozone as well as their role in conduction of electricity through the atmosphere. In particular Tesla is well known as the first person to produce rf plasmas. Such plasmas in the present day constitute the main technology required to produce integrated circuits (IC) and have been essential in the revolution that resulted from IC technologies. In addition Tesla participated in studies of arcs especially arcs used as a source of light, corona discharges required to induce plasma chemical reactions and produce ozone and was involved in various aspects of gas breakdown and gaseous dielectrics. His ideas, level of his understanding and current status of these fields are discussed in this review.

Keywords: RF plasmas, Inductively coupled plasmas, capacitively coupled plasmas, amera-ready paper, Proceedings of papers, TELSIKS ′05.

1 Introduction

Nikola Tesla is widely recognized as one of the founders of the studies of RF plasmas [1-3]. Very few scientists may support their priority in discovery by a photo as dramatic as that of Tesla sitting and reading right next to a large Tesla coil which produces a lot of sparks (see Fig. 1). Even though it is well known that it was a trick photo made by using a double exposure the point is made clearly and directly. Tesla’s claim to fame in plasma physics and gaseous electronics is not limited only to the fact that he was the first to produce high-voltage high-frequency transformers and that those transformers produced a lot of sparks in the air.

Tesla made some systematic studies of gaseous electronics, gas discharges and gas plasmas, particularly in relation to their applications. Tesla’s interests in plasma physics include first of all rf breakdown and rf discharges, then he was interested in breakdown at low pressures and glow discharges, application of those discharges in light sources (Geissler tubes) was one of his favourite subjects as well as application of atmospheric arc plasmas as a light source.

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Finally he did research in ozone production by a discharge that he patented and in the fundamental studies extended the measurements to very low pressures. All of these topics are of interest even today and while covering his work we shall also make a review of the current status of development, future interests. Our particular focus will be on the contribution of groups from Serbia to those fields Laboratory for Gaseous electronics of the Institute of physics Belgrade in particular.

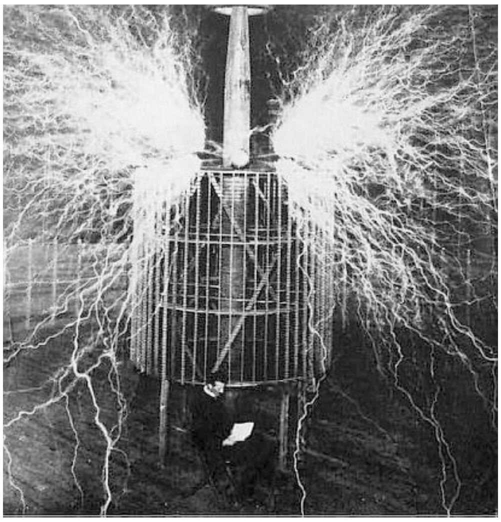

Fig. 1 – *Famous photo of Tesla with his coil producing a large number of sparks in the laboratory. Photo was apparently made by double exposure.*

2 RF Discharges and Breakdown

A. Tesla's studies of gas discharges and plasmas

Tesla's papers are not as focused as those which are produced today. They seem more like general progress reports covering the whole field that is the focus of his research. The information on plasmas is also hidden in patents and one needs to read the whole thing.

The first class of his studies deals with discharges in the air related to the high voltage coils. The discharge was often taken as a sign of the existing high voltage. In Fig. 2 we show an example of Tesla oscillator producing plasma. Tesla has discussed the development of the discharge between two sharp peaks connected to a high voltage difference at very high frequency [5]. He described transition form a single filament to a relatively large volume plasma (see Fig. 3) although it is not certain whether the changes are due to real broadening of the plasma cross section or due to motion of the filament. Most importantly Tesla puts a layer of glass in between two electrodes and the discharge is uninterrupted (see Fig. 4) thereby demonstrating the first capacitively coupled discharge. It is interesting to note that in description of the developments Tesla often uses visual images and their schematics. He even uses esthetical criteria in descriptions. One could perhaps argue that tat that level of phenomenology and almost complete lack of fundamental understanding and theory he could not do much more. However, even in the present day plasmas are often described by similar methods and a special issue of IEEE Transactions on Plasma science has been initiated by Mark J. Kushner to publish short papers where images are worth a thousand words and have to meet esthetical criteria as well (one example of a paper form one of those issues is given in [6]). Tesla's images and drawings would have been perfect candidates for such publications.

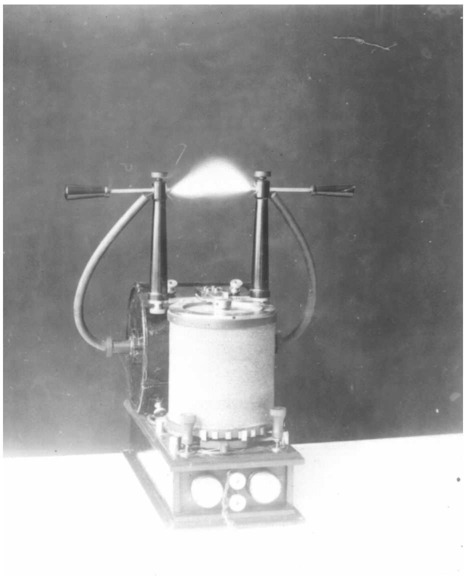

Fig. 2 – *Tesla's oscillator which provides a strong source of emission due to plasma* [4].

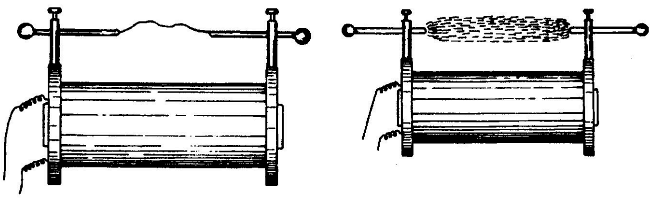

Fig. 3 – *Schematics of plasma development from a Tesla's oscillator with an increase of the current* [5].

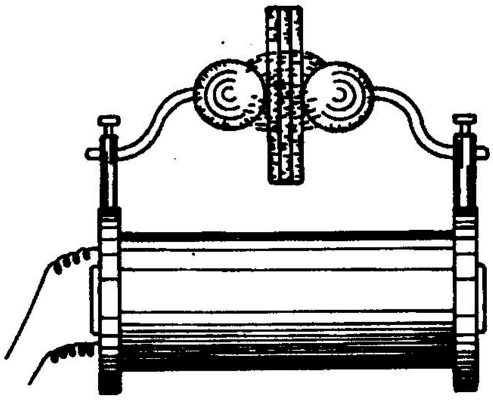

Fig. 4 – *The effect of dielectric on the rf discharge in the air* [5].

The other line of Tesla's research in gas discharge physics was related to the low pressure discharges (plasmas). In his lecture [7] on Light and other high frequency phenomena Tesla shows, among other things, a number of examples of low pressure tubes that were excited by high-frequency high-voltage sources. The most illustrative is certainly his standard photograph where a low pressure is held in the field of high voltage coil and it lights up without any direct electrical contacts. Such devices are precursors of the inductively coupled plasmas that will be discussed later in context of applications to plasma etching. The same lecture [7,8] discusses atmospheric pressure plasmas where, for example, just holding a conductor in the field of the coil provides luminous layer around the conductor as a result of a high frequency corona discharge.

Tesla has provided numerous results with low pressure tubes, Geissler tubes and other low pressure systems. He has shaped the tubes in complex arrangements and also was the first to use high frequency power supplies to produce non-equilibrium plasmas. One such system is shown in Fig. 5.

It is interesting to note two things. The first is that Tesla had several exchanges of critical comments (in both directions) with J.J. Thomson (the Nobel prize winner and leader of the Cavendish Laboratory from Cambridge- and the discoverer of electron) on the issues of gas discharges. Mostly problems were in different terminologies but in some of the issues the two great men of science had opposite views. Needless to say that time has shown that the picture is usually much more complex that envisaged at that stage so one cannot declare the winner of the debate. The second issue is that one of the items that Tesla is very well known and still often mentioned in the Laboratories around the world is the use of Tesla coil to test whether there is gas in glass tubes by inducing a discharge in them. This technique is wide spread and will continue to be a standard laboratory technique for vacuum systems.

Tesla has worked on other types of discharges such as arcs or ozonizers, which will be discussed later in separate sections.

Fig. 5 – *Tesla's system of glass tubes for losw pressure discharge excited by RF source.*

B. RF breakdown at atmospheric and low pressures

Before producing a plasma one needs to convert the background gas which is a dielectric into a conductor or in other words to ionize it. Tesla studied discharges well before they become a science which happened with the work of Townsend on breakdown and low current discharges and with the work of Langmuir on plasma properties and sheaths. These studies were conducted in the first 20 years of the 20th century. Nevertheless Tesla had to consider the basic phenomenology of the breakdown, it was certainly an essential part of many of his studies but mostly in attempts to avoid the breakdown.

More detailed and fundamental understanding of gas breakdown has been achieved recently for dc fields [9]. While some degree of understanding of the rf breakdown exist only recently studies have commenced and led to further improvements of the rf breakdown [10,11] and microwave breakdown theories. In Fig. 6 we show an example of the so-called Paschen curve for rf breakdown representing the dependence of the breakdown voltage on the product of pressure and gap between electrodes *pd*. With results like those one may start to distinguish between different breakdown mechanisms, classical Townsend breakdown, streamer and runaway electron breakdown and in case of rf the additional multipactor mechanism. Those mechanisms were only partially known to Tesla and only at a phenomenological level. Nevertheless he managed to take advantage of such knowledge to optimize his work on high voltage and high frequency devices and in some cases their application to gas discharges and plasmas.

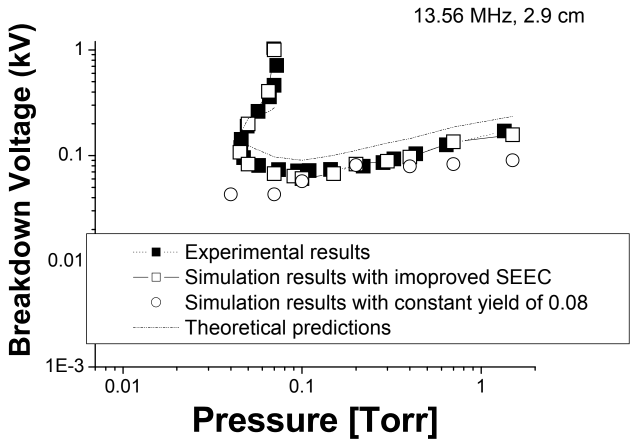

Fig. 6 – *Paschen curve for breakdown of argon in rf field* [10] *as a function of pressure for a fixed gap between electrodes. Experimental results* [11] *are compared to simulations with different models of secondary electron emission. The best results were obtained by using the model of secondary emission from* [9].

C. Applications of RF discharges and current level of research

When considering plasmas two types have to be distinguished. The first are thermal plasmas and those mainly conform to thermal distributions and very basic and general laws such as Boltzmann's energy distribution and Saha equation. However, plasmas are seldom in equilibrium and often in such plasmas a local thermal equilibrium is assumed where the temperature is merely a convenient parameter. The thermal nature of such plasmas is, however, obvious from the fact that the same temperature describes properties of all particles including electrons and heavy particles.

In case of non-equilibrium or non-thermal or low temperature plasmas the situation is exactly the opposite. There we try to control only the energy of electrons by electric field in order to initiate ionization and dissociation and of course the excitation so that plasma may be sustained, may be a source of chemically active species or light. We can achieve that by separating the ion and electron kinetics by taking into advantage a very large difference in mass between electrons and molecules. Thus electrons transfer almost no kinetic energy in the recoil and the only considerable energy transfer is due to inelastic collisions. If one wants to produce non-equilibrium plasmas one has to keep the degree of ionization very low in order to reduce the Coulomb coupling between ions and electrons. This is difficult to achieve at atmospheric pressure due to a large number of collisions and consequently very rapid ionization so the optimum conditions for non-equilibrium plasmas are low pressures.

The basic characteristics of non-equilibrium plasmas are the result of the fact that they operate under conditions when electron energies (temperatures) are quite high while the energies of ions and gas molecules correspond to the room temperature. This electrons initiate numerous processes that have a high energy threshold. The most important are ionization which maintains plasma and dissociation which leads to reactive radicals.

Between plasma and the walls a sheath develops. The high field in the sheath is required to prevent electrons from escaping the plasma. Thus the sheath slows electrons down and in addition it accelerates the thermal ions so that the fluxes of ions and electrons to the surfaces are equal. In other words ions enter the sheath with low energy ions and after gaining velocity they arrive at the surface at the right angle. At the same time radicals which are also produced by the plasma, and which are neutral, cover both the bottom and the sidewalls of the trench. Thus combination of the effect of ions and radicals will give a very rapid and directed etching that will enable us to achieve very small structures in the nanometer range. The property of the non-equilibrium plasmas that the ions are at a room temperature while the electrons are at high temperatures is the basis for high resolution etching that has provided us with all the submicron technologies and has fueled the growth of electronic industry for the past 30 years. Thus it has been the basis of the so called Moore’s law which epitomizes the growth of electronics to the number one spot in the world trade and economy.

Another property of the non-equilibrium plasmas is that almost all energy is converted to the electron energy and subsequently spent on ionization, excitation and dissociation of molecules. Thus the efficiency in achieving plasma chemical reactions is improved as compared to thermal plasmas where most of the energy is spent on heating of the gas and the reactor walls. Low temperature of the gas allows us to treat thermally unstable materials such as polymers, organic materials, living matter even human tissue in vivo.

D. RF plasmas reactors

The development of the plasma devices for IC production and most other applications has been mainly empirical even until very recent times. The need to treat both conductors, dielectrics and semiconductors led to the application of rf plasmas. Predominant plasma sources today are capacitively coupled plasmas (CCP) and inductively coupled plasmas (ICP).

ICPs appear to be direct descendents of the low pressure rf discharges studied by Tesla. ICPs are used widely in the present day industry mainly for etching of the poly silicon andmetals. Their main advantage is that due to lack of electrodes and the resulting reduced losses a high density of charged particles is achieved [3,12]. As a result, radicals and excited states [12] are present at higher densities as compared to CCPs. This changes the properties of the plasma facilitating ionization and thereby reducing the mean electron energy [9]. It is possible to have a special design of coils that will make it possible to achieve uniformity over large areas.

Etching of SiO_2 in IC manufacturing amounts to approximately 80% of the steps in production due to complex and numerous interconnects. Typical mixture that is used for this purpose is Ar-CF_4. Etching of silicon and SiO_2 is non-linear with a threshold for the ion energy of around 100 eV and with saturation at above 800 eV. The energy is needed to break the Si bonds and make it accessible to F atoms which are adsorbed to the surface. However, the fragments that were detached from the surface may polymerize and protective layers may form on the side walls.

The CCPs were also described by Tesla. Insertion of a glass between two electrodes producing rf plasma did not turn the discharge off, it continued on both sides of the glass. CCPs are maintained either by reflection of electrons from the moving sheath boundary (the so called α mechanism) and at somewhat higher powers by electrons formed at the instantaneous cathode and accelerated through the sheath (the so called γ mechanism) [12]. If negative ions are present double layer formation leads to the highest contribution to ionization.

The future of IC manufacture apparently belongs to CCPs. is the current message from the industry which has shown interest in funding further research in CCPs. In particular, all research regarding pulsed two and three frequency operation is regarded as topical and the key issue is whether functional separation is achieved between the plasma driving source and the source for accelerating the ions. Much higher frequencies than the standard 13.56 MHz must be sought to achieve functional separation [13] for CCPs while the situation is less critical for ICPs [14]. Further advances of plasma sources requires development of comprehensive plasma modelling tools [3]. This on the other hand requires a good knowledge of electron, ion and radical transport and collision data and also of the related kinetic phenomena [15].

D. Micro discharges at low and at atmospheric pressure

It has already been explained why non-equilibrium plasmas are most easily maintained at low pressures. However, if we start from the Paschen curve and extrapolate to atmospheric pressures gaps of the order of 1 μm are required to be at the minimum of the breakdown voltage. Thus if one wants to operate at atmospheric pressure under non-equilibrium conditions there are two options:

a) To prevent transition to arc or thermal plasma. Techniques to avoid this development and achieve non-equilibrium conditions consist of interrupting the discharge either temporally (pulsed or high frequency discharges), or by inhomogeneous electric field (corona) or by a dielectric barrier (dielectric barrier discharge).
b) Another way to achieve atmospheric pressure non-equilibrium discharges which are still is to operate at very small gaps which have to be of the order of few microns or less in order to achieve minimum breakdown voltage and stable operation under low temperature conditions.

The initial motivation for these studies came from the need to optimize plasma screens. but new applications were developed very rapidly.

In recent years, a variety of microplasma sources with potential use in different portable devices have been reported: Microplasma sources operating in the capacitively coupled mode and the inductively coupled mode have also been miniaturized.

Medicine and biology are among the most promising applications of microplasmas, but the same time most challenging. Four important areas of application of MST in medicine and biology may be specified: 1) diagnostics, 2) drug delivery, 3) neutral prosthetics and tissue engineering and 4) minimally invasive surgery. Micro discharges may play and important role especially in tissue engineering and in minimally invasive surgery.

The recently developed device known as plasma needle [16] is a typical example of capacitively coupled rf discharge that was developed for applications in medicine. The dimensions of the discharge are not too small but of the order of 1 mm and the plasma is sustained by an RF field. So in this case non-equilibrium nature of plasma is achieved by a combination of strategies. In Fig. 7 we show a plasma needle developed at the Institute of Physics in Belgrade.

3 Arcs and Light Sources

Arc light sources were well known in Tesla's time. He considered several very practical issues such as control of position of electrodes during staring of the arc and its operation [17,18]. Another Tesla's patent deals with operation of low and high frequency arc lamps. Tesla's has observed that by adjusting frequency one may reduce the noise produce by time dependent oscillation of hot air produced by plasma. Simple transition to frequencies higher than the range of a human ear [19] could reduce unpleasant side effects for humans though dogs and other animals would welcome further increase in frequency. In any case Tesla may be regarded as the first person to develop high frequency arc discharges.

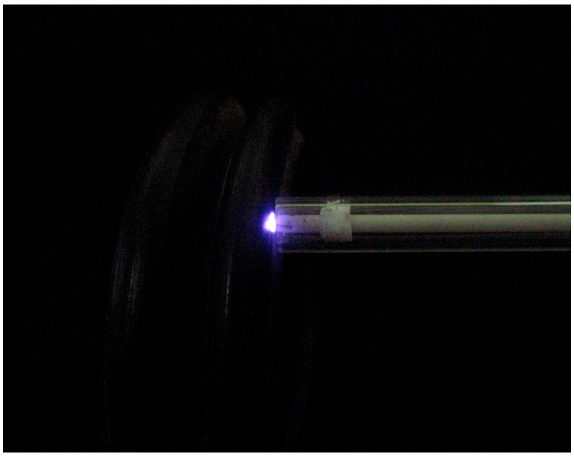

Fig. 7 – *Plasma needle* (*Institute of Physics, Belgrade*) [16].

Arcs are often used in modern technologies. The type of arcs as those considered by Tesla are more often used for thermal plasma chemical treatment of materials, such as gasification of coal, waste treatment and treatment of materials. Very often light from such arcs is used for analytic purposes but even in this application arcs are being replaced by thermal ICPs. Sometimes arc lamps are used even for absolute calibration and in any case arc lamps are the strongest sources of light that are commercially available. Finally, more modern applications such as pulsed YAG lasers require pumping by strong light sources and pulsed arcs are standard sources used for laser pumping.

In Serbia and former Yugoslavia, studies of arcs as spectroscopic sources and analytic tools have been carried out at Faculty of chemical Physics (prof. Vukanović), Faculty of Electrical Engineering (Prof M.S. Todorović), Vinča Institute and Institute of Physics of the University of Belgrade and also in University of Novi Sad. Production of pulsed arc lamps was developed on the basis of the scientific research at the Institute of Physics Belgrade.

Regardless of the fact that his interests in lighting were directed towards Geissler tubes (low pressure glow discharges) and arcs it is Tesla's work on development of rf discharges that has the longest lasting legacy in plasma applications [20]. The most efficient, longest lasting lamps are inductively coupled sources operating in the Megahertz range. Having in mind number of light sources continuously in use on the planet, any increase in efficiency, regardless of how small it is translates into huge global energy savings. Thus this field of research is very much alive today and the current issues include development of new background gases that would not involve mercury and other gases which are dangerous for the environment and hazardous for humans.

4 Ozone Production

A very interesting apparatus is presented in on of Tesla's patents [21]. It is essentially a device for producing ozone. The schematic drawing is shown in Fig. 8. In this device air flow is maintained between two wires connected to high voltage provided by a condenser and a coil. A corona like discharge is produced between the wires. The discharge is able to initiate a number of plasma chemical reactions leading to production of the ozone. Most importantly Tesla is aware that this only a single implementation of the device and that it has a potential to be used to initiate other chains of plasma chemical events leading to different products and applications. At the present day such device could be the basis for ionizers or air purifiers that are at the moment fashionable but may become necessary in near future. In addition the potential of such an apparatus for removal of pollutants including gases such as NO, NO_2, SO_2 and micro organisms.

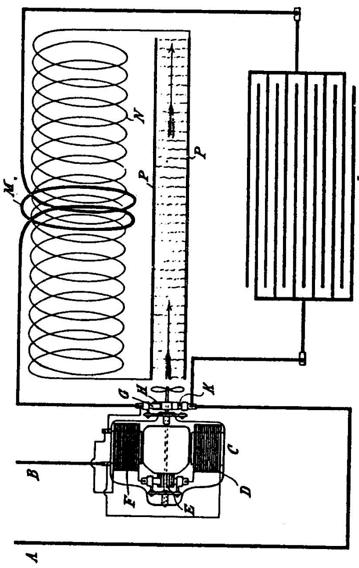

Fig. 8 – *Tesla's device to produce ozone by initiating a chain of plasma chemical reactions* [21].

5 Atmospheric Breakdown-Lightning protection

In his patent [22] Tesla proposed a new principle for lightning protection. Instead of inducing the discharge to a well grounded object he proposes to actually develop a shape of the protecting surface in such a way that the field will be below the breakdown field required to initiate corona or streamer discharges. While this proposal may not be practical for the intended purpose due to large required size and meteorological and other reasons, the calculation given in the patent and general consideration show understanding of the phenomena of the atmospheric breakdown (distinction between streamers and coronas). In addition the practical application of such a device would be of interest for number of applications and similar devices exist.

Tesla's interest in lightning protection and atmospheric breakdown appears to have been motivated by his long term interest to achieve transmission of electrical power through natural media. In fact he claims exactly the opposite [23]. The idea of using natural media to conduct power came from observing the effect of lightning on electrical instruments during his studies of atmospheric discharges. During those studies he found standing waves in the earth and the response of instruments was strongly dependent on their position.

6 Conclusion

Plasmas provide a basis to achieve many different processes by merely changing background gas, frequency, voltage, current or composition of the gas mixture. [3,5,6]. Amongst the most versatile and most generally used are the rf plasmas and having in mind the market of modern electronic devices they certainly have the largest share. Having in mind the impact of modern integrated electronics in all areas of human life we may safely say that the use of non-equilibrium rf plasmas (together with other required technologies such as photolithography, thin film deposition and implantation) has changed the civilization more than any other technology in the past 40 years. While Tesla's contribution as initiator of rf discharges is significant the present day applications and developments are well beyond the grasp of his research and one should limit praises merely to the statement: *Tesla was the first to produce and to some small degree study rf gas discharges and plasmas*.

In addition to the relevance for IC production Tesla's research still affects or at least can be correlated to topical studies of arcs, lighting sources, ozonizers, air purifiers and many more applications of non-equilibrium and thermal plasmas.

7 Acknowledgement

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8 References

[1] Yu.P. Raizer: Gas discharge Physics, New York Springer Verlag, 1997.

[2] T. Makabe and Z. Lj. Petrović: Development of optical computerized tomography in capacitively coupled plasmas and inductively coupled plasmas for plasma etching, Appl. Surf. Sci., vol. 192, pp. 88-114, 2002

[3] T. Makabe and Z.Lj.Petrović: Plasma Electronics, New York Taylor and Francis CCR Press (2006).

[4] N. Tesla: Patent specification 649 621 (1900), Nikola Tesla: Sabrana dela – Patenti II, Zavod za izdavanje udžbenika, Beograd (1996), p. 408.

[5] N. Tesla: Experiments with alternating currents at high frequency and their application in artificial lighting 1891. Nikola Tesla sabrana dela Predavanja Zavod za izdavanje udžbenika Beograd (1996) p.41: also in Electrical Engineer NY vol. 18 (1891) and AIEE transactions, Vol. 8, pp. 267 1981.

[6] S. Bzenić, Z.M. Raspopović, S. Sakadžić and Z.Lj. Petrović: Relaxation of Electron Swarm Energy Distribution Functions in Time-Varying Fields, IEEE Trans. Plasma Sci., vol. 27, pp. 78-79 1999.

[7] N. Tesla: On Light and other high frequency phenomena 1893, Nikola Tesla: Sabrana dela – Predavanja, Zavod za izdavanje udžbenika, Beograd (1996), p.167; also in Journal of Franklin Institute, Philadelphia, July 1993.

[8] N. Tesla: High frequency oscillators and control of electrical circuits 1897, Nikola Tesla: Sabrana dela – Predavanja, Zavod za izdavanje udžbenika, Beograd (1996), p.251; also in New York Academy of Science, April 6, 1897.

[9] A.V. Phelps and Z.Lj. Petrović: Cold cathode discharges and breakdown in argon: Surface and gas phase production of secondary electrons, Plasma Sources Sci. Technol., vol. 8, pp. R21–R44, 1999.

[10] M. Radmilovic-Radjenovic and J.K. Lee: Modeling of breakdown behavior in radio-frequency argon discharges with improved secondary emission model Phys. of Plasmas, vol. 12, 063501, 2005.

[11] N.Yu. Kropotov, Yu.A. Kachanov, A.G. Reuka, V.A. Lisovskiy, V.D. Erorenkov and V. Farenik: Breakdown of low-pressure gas in uniform rf field, Sov. Tech. Phys. Lett. Vol. 14, pp.159-160, 1988.

[12] N. Nakano, N. Shimura, Z.Lj. Petrović, and T. Makabe: Simulations of RF glow discharges in SF6 by the relaxation continuum model: Physical model and function of the narrow gap reactive-ion plasma etcher, Phys.Rev. E, vol. 49, no. 5b, pp. 4455–4465, 1994

[13] T. Kitajima, Y. Takeo, Z.Lj. Petrović and T. Makabe: Functional separation of biasing and sustaining voltages in two frequency capacitively coupled plasma, Appl. Phys. Lett., vol. 77, pp. 489-491, 2000.

[14] T. Denda, Y. Miyoshi, Y. Komukai, T. Goto, Z.Lj. Petrović and T.Makabe: Functional separation in two frequency operation of an inductively coupled plasma, J. Appl. Phys., vol. 95, pp. 870-876, 2004.

[15] Z.Lj. Petrović, Z.M. Raspopović, S. Dujko and T. Makabe: Kinetic Phenomena in Electron Transport in Radio Frequency Fields Appl.Surf. Sci,. vol. 192, pp. 1-25, 2002.

[16] N Puač, Z.Lj Petrović, G. Malović, A. Đordević, S. Živković, Z. Giba and D. Grubišić: Measurements of voltage–current characteristics of a plasma needle and its effect on plant cells, J. Phys. D: Appl. Phys., Vol. 39, pp. 3514–3519, 2006.

[17] N.Tesla: Patent specification 335 786 (1886), Nikola Tesla: Sabrana dela – Patenti I, Zavod za izdavanje udžbenika, Beograd (1996), p. 20.

[18] N.Tesla: Patent specification 335 787 (1886), Nikola Tesla: Sabrana dela – Patenti I, Zavod za izdavanje udžbenika, Beograd (1996), p. 52.

[19] N.Tesla: Patent specification 447 920 (1891), Nikola Tesla: Sabrana dela – Patenti II, Zavod za izdavanje udžbenika, Beograd (1996), p. 80.

[20] G.G. Lister, J.E. Lawler, W.P. Lapatovich, and V.A. Godyak: The physics of discharge lamps, Rev. Mod. Phys. vol. 76, pp. 541, 2004.

[21] N. Tesla: Patent specification 568 177 (1886), Nikola Tesla: Sabrana dela – Patenti II, Zavod za izdavanje udžbenika, Beograd (1996), p. 286.

[22] N.Tesla: Patent specification 1 266 175 (1918), Nikola Tesla: Sabrana dela – Patenti IV, Zavod za izdavanje udžbenika, Beograd (1996), p. 100.

[23] N.Tesla: Patent specification 1 266 175 (1918), Nikola Tesla: Sabrana dela – Patenti III, Zavod za izdavanje udžbenika, Beograd (1996), p. 250.