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# NON-EQUILIBRIUM PLASMAS IN TELECOMMUNICATION RELATED TECHNOLOGIES

**Zoran Lj. Petrović, Zoran M. Raspopović
and Toshiaki Makabe**

**Abstract:** In this paper we give a review of some of the recent advances in modeling of ionized gases and their implications in telecommunications. In particular we discuss the gas breakdown due to rf and microwave fields, the multipacting discharges and the rf discharges used for integrated circuit processing

**Key words:** Plasma, gas discharges, plasma processing, multipacting discharges, atmosphere, electron swarms, transport coefficients, gas breakdown, integrated circuit technologies.

## 1. Introduction

The development of telecommunications in its very early days was very strongly associated with the physics of ionized gases and charged particle swarm physics. The very discovery of electron by J.J.Thomson in 1897. was achieved by developing an experiment which turned out to be a prototype of a Cathode Ray Tube. The discovery was, however, supported by the first measurements of the elementary charge by J.Townsend in a device that gave birth to Wilson's cloud chamber (and consequently to the development of nuclear physics) and measurement of transport properties of electrons which gave birth to the physics of swarms of charged particles. In its basic form the scientific endeavor was formulated as an attempt to explain the cathode rays,

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Z. Petrović and Z. Raspopović are with University of Belgrade, Institute of Physics, P.O. Box 68, 11080, Zemun, Belgrade, Yugoslavia (e-mail: `zoran@phy.bg.ac.yu`). Z. Petrović is also at Keio University, Department of Electronics and Electrical Engineering, 3-14-1 Hiyoshi, Yokohama 223-8522, Japan. T. Makabe is with Keio University, Department of Electronics and Electrical Engineering, 3-14-1 Hiyoshi, Yokohama 223-8522, Japan.

which have been observed in low pressure discharges. On the other hand the first observations of the transmission of electromagnetic waves involved formation of sparks in the air. Most importantly the two fields converged together in the first half of the 20th century since the main motivation of the charged particle swarm studies (and atomic and molecular collision physics in general) in that period appeared to be the need to describe the ionization and plasma chemical processes in the atmosphere.

In this presentation we will try to illustrate how these two fields interact at present and what are possible future points of common interest.

First we shall discuss the effect of multipacting discharges which seem to be one of the more serious problems in microwave devices, though sometimes they may be even used for modulation of microwave sources. The second issue that will be discussed here is modeling of charged particle transport in high frequency fields and the new kinetic phenomena that are associated with electron transport in time varying fields. These issues have their importance in discussing propagation of electromagnetic waves through the atmosphere and formation of ionized gas for induced plasma chemical applications and for over the horizon applications. Finally we shall discuss the issues associated with application of rf plasmas in integrated circuit production and the limits in growth of the power of microprocessors as massive processing power becomes the requirement for the new generation of telecommunication devices.

## 2. The Basics of Physics of Ionized Gases

Under normal conditions the gases as we know them are dielectrics, as we may prove by the mere fact that we are not constantly hit by electric shocks or as a matter of fact by the possibility that sometimes we may be shocked by high voltage. Yet we have all observed that gases become excellent conductors to such a degree that they are often used as a medium in high power switching.

The conduction of electricity in gases is associated of course with the production of free charge carriers, electrons and ions and the kinetics of production and losses is the key issue in maintenance of plasma. The distinction is important between gases ionized by some external source of ionization and those that may be able to sustain themselves purely under the influence of the electric field that is causing the current flow. Thus we differ self-sustained and non-self-sustained discharge.

At the low charge density end of the ionized gases scale lie swarms of particles. These discharges occur at such low currents that the density of the charges is insufficient to affect the external electric field significantly. The transport of charge occurs under the influence of external field from which they gain the energy and under the influence of collisions with molecules of the carrier gas in which they lose their energy. It is often assumed that when they collide with the particles of the gas they do that so infrequently that no influence of the previous collisions may be observed on the molecular target, all the excitations are relaxed and the kinetic energy dissipated. The key issue in swarm studies is that of collisions, because such experiments and theory allow us to determine very accurately the cross sections and rate coefficients for particular processes. The transport theory and especially the non-hydrodynamic or the non-local transport still pose interesting and unresolved scientific issues that require further research. Swarm conditions are normally achieved in non- selfsustained and in selfsustained discharges operating in the dark Townsend regime [1]-[4].

In the second stage, at higher currents, the charged particles accumulate and affect the field distribution through shielding mostly though now it is quite common for electrons to collide with excited molecules [5]-[8]. The complex field distribution that arises can be determined only self- consistently thus we have to settle all the issues of the collision probabilities and transport at the level of swarms before attempting to describe such ionized gases that may already be characterized as plasmas. These plasmas range from highly collisional to weakly collisional. Their general characteristic is that in the complex field distribution that arises there are limited regions where ionization, required to sustain the discharge, occurs. Normally those regions are right at the boundary of the plasma, at the edge of the sheath where most of the voltage drop is. Such conditions are found in normal glow and abnormal glow discharges. They also begin to show collective phenomena due to long range Coulomb interaction but the electron energy distribution function is still non- Maxwellian.

Finally at relatively high charged particle densities collisions start losing their importance while long range interactions open Pandora's box of numerous modes, waves and other collective phenomena. Unfortunately most of these are better understood from the theoretical point of view where nonlinear equations give a myriad of mathematically interesting solutions, while the experiments were made only on a very limited number of the most important modes and waves. These conditions are usually known as plasma physics and it is usually neglected that collisional non-equilibrium plasmas also satisfy the conditions for being a plasma. The key issue for telecommunications in plasma physics is its ability to reflect the electromagnetic waves with frequencies lower than some limit determined by the plasma density of charged particles. While we have the natural plasma shield around the earth, caused by ionospheric plasma sustained by solar radiation, in some more recent "experiments" attempts have been made either to create similar plasma elsewhere in the atmosphere or to perturb the natural ionosphere. In those experiments kinetics of production of the ionized gas becomes the key issue and considerations must focus on physics of collisional plasmas and swarms rather than the physics of collective phenomena in plasmas which is the standard approach.

## 3. Multipacting Discharges

Multipacting discharges have been known for some time [9]-[11]. These discharges are maintained by the production of charges in collisions of high energy electrons with surfaces. Thus they may even occur in complete vacuum. Normally they require rf field and in that field the group of electrons that travels between the two electrodes in the half period of the field is accelerated in both directions and oscillates between the electrodes. Higher order modes ($(2n+1)T/2$ where $T$ is the period of the field) are also possible. At high electron energies reflection of electrons is high and the probability of secondary electron production is even higher. Thus electrons may multiply and a discharge may begin to grow. Multipacting discharges often occur in waveguides at low pressures so satellite communications may be affected. However multipacting is even possible in gas discharges for relatively low pressures either as the dominant or partial mechanism of ionization [12]. In Fig. 1 we show results of our modeling of a multipactor discharge at extremely low pressure, practically in vacuum.

In Fig. 1 the phase space diagram shows two electrodes with a large positive voltage on the right hand side. The secondary electrons formed at the instantaneous cathode are accelerated into the gap while those formed at the anode are trapped right next to the anode or return to it. They will be released at the moment when the direction of the field changes and will be accelerated into the gap. The electrons inside the gap are accelerated towards the anode. That may be observed from their extended distribution towards positive velocities, while negative velocities are reduced towards zero. Thus several modes form in the resonator.

The simulation was performed by using a standard particle in cell (PIC) code [13], [14]. This code allows following the trajectories and other properties of a limited number of particles while at the same time through renormalization of the effective charge realistic field distribution may be determined.

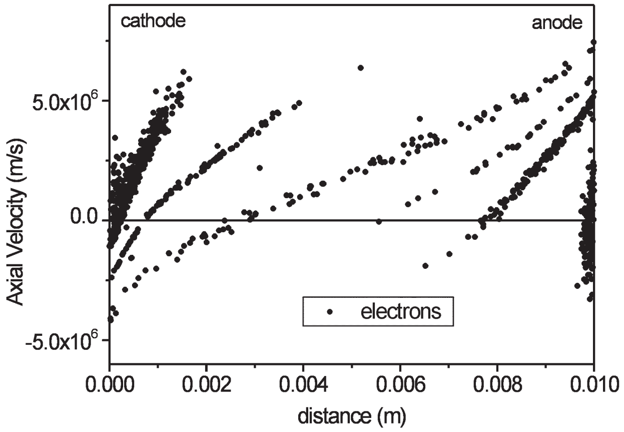


*Fig. 1. Phase space diagram of different modes in a multipacting discharge. Calculation was performed for 1.356 GHz supply with a peak voltage of 1000 V.*

The distribution of field shows that the space charge in the gap shields the external field significantly and thus limits the further growth of the charge. In Fig. 2 we show the distribution of the field inside the gap for the same conditions as in Fig. 1 though not for exactly the same phase.

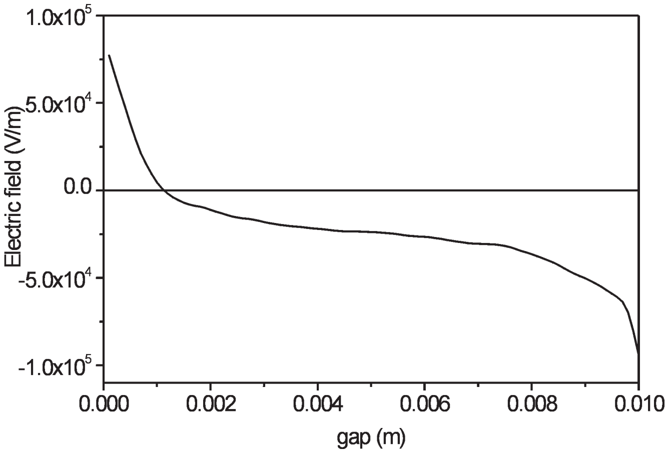


*Fig. 2. Distribution of the electric field in a multipactor discharge for the same conditions as in Fig. 1. though for a different phase.*

In models of multipactors that were used so far, and such model has been shown above, reflection of electrons is assumed to be a simple process of reflection with a probability that new electrons may be created. However, the collisions of electrons with the surface may lead to elastic scattering, inelastic scattering and production of secondaries, resulting in a broad and complex spectrum of reflected particles [15], [16].

### 3.1. Modeling of electron reflection in gas discharges

We have attempted to include the actual properties of reflected electrons in gas discharge models. The model had to take into account [17], [18]:

1. angle of incidence and its effect on all parameters,
2. angular distribution of reflected particles,
3. angular distribution of secondary electrons,
4. energy of incidence,
5. energy loss in collision with the surface,
6. character of the surface,
7. material of the surface,
8. energy spectrum of reflected particles,
9. energy spectrum of secondary particles and
10. proper normalization of the secondary electron production and reflection coefficients.

The first test that we performed was to apply such realistic model of reflection to gas discharges operating under dc fields [18], [19]. For example it was assumed that the sharp peak close to the anode that was observed at high $E/N$ (where $E$ is the electric field and $N$ is the gas number density- the units of Townsend are used 1 Td= $10^{-21}\mathrm{Vm}^2$) is caused by the excitation due to reflected electrons [19]. We have used the well defined and absolutely normalized experimental data for spatial emission profiles to verify both the assumption and the accuracy of the model. In Fig. 3 we show the spatial profiles of emission that were calculated together with the experimental data.

While one may argue that the peak close to the anode is quite small it actually may contribute to a large additional ionization. The direct electrons at very low pressure conditions gain very quickly energies that are higher than those of the maximum of the ionization cross section. The reflected electrons that slow down actually reach the energies of the maximum ionization probability. We have obtained increases of between 30% and 100% in the overall multiplication for realistic breakdown conditions at low pressures [17].

The peak close to the anode is very sensitive to the chosen material and details of the modeling of reflection. The peak obtained in model and

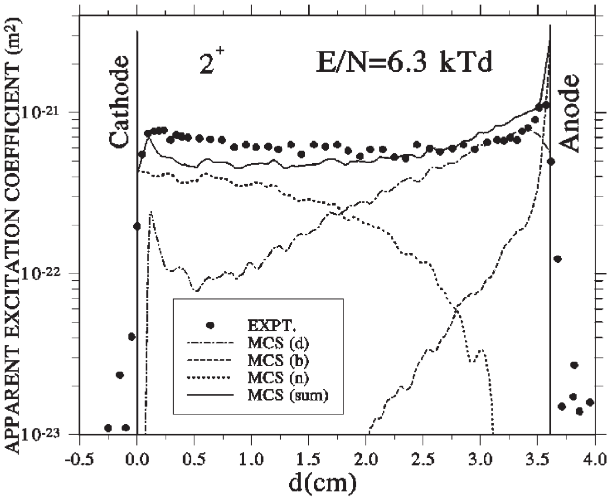


*Fig. 3. The spatial emission profiles (normalized to excitation coefficient) obtained in a low pressure low-current discharge in $N_2$ at very high E/N value of 6.3 kTd. Experimental data are shown as points and the simulation provides the contributions of direct (d) electrons, fast neutrals (n) and reflected or back scattered electrons (b) [18].*

shown in Fig. 3 represents the experimental data very well. The modeling provides a much sharper peak but one should bear in mind that experimental data are obtained with a limited spatial resolution so the integral effect should be considered and the representation of the experimental data with the best available data in the literature without any adjustments is very good. This gives us a confidence that application of the more complex model of reflection for multipactors will provide more reliable data since, in those circumstances, there are no ways to verify the applicability of the reflection model. In particular we hope to be able to prove that the model is capable of accurately representing the material that is used for the surface which may replace the very expensive experimental studies of the effect of multipacting discharges in practical devices for satellite communications [11].

## 4. Electron Transport in RF Fields

Most of the understanding of the electron transport in gases was based on DC studies in swarm physics where accurate methods for calculation of electron energy distribution functions (EEDF) were tested by comparisons of results for well-defined models. In addition, accurate swarm experiments to provide basis for normalization of the cross sections. For rf fields it was

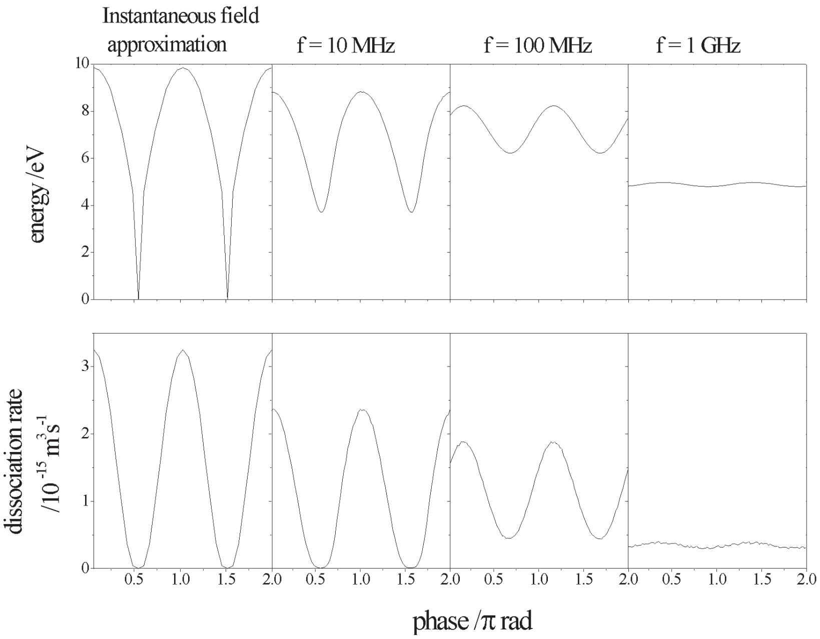


*Fig. 4. Quasi stationary phase dependencies of the mean energy of electrons and of the dissociation rate for different frequencies and instantaneous field (quasi DC) approximation. Simulations were performed in pure $CF_4$ at 1 Torr (50 km of altitude) and at $E/N$=200 Td ($E$=70 V/cm) with cosine time dependence of the field. The drop in the ionization efficiency is even more significant and it is caused by the high threshold for ionization and dissociation and the fact that at high frequencies the high energy tail of EEDF is reduced. At the same time the mean energy is not affected much by the increase in frequency and also are not affected the drift velocity and the elastic collision rate. [24]*

assumed that instantaneous field approximation may be used and even more often an approximation of the effective DC field was employed [20]. Implicit in those theories was an additional approximation that hydrodynamic expansion is valid in time varying fields for the quasi steady state distribution (i.e. the distribution that varies with the phase but not from phase to phase). Finally some attempts were made to produce approximate theories for time varying electric field, yet even those data were not employed in plasma models which are still mainly dependent on the dc transport data.

Recently however, exact theories of transport [21], [22] and Monte Carlo codes [23] were developed for rapidly varying electric field. There it was found that a number of new kinetic phenomena exist that may not be well represented by quasi dc theories and even by the theories of limited accuracy for time varying fields.

These theories have to be employed in modeling of rf plasmas of all types. In this paper we shall mention how these new phenomena affect the breakdown in gases, how they affect the interaction of electromagnetic wave and weakly ionized gas and how modeling of transport in (ExB) fields may be accomplished.

### 4.1. Modeling of the gas breakdown in gases

The effective field approximation may be defined through the DC value of $E/N$ that would result in the same overall rates as in the rf fields $E(t) = E_0 \cos(\omega t)$

$$E/N(eff) = \frac{E_0/N}{\sqrt{2}\sqrt{1+\frac{\omega^2}{\nu^2}}} \tag{1}$$

Here $E_0$ denotes the amplitude, $\omega$ the angular frequency of the field and $\nu$ the collision frequency [24]. Sometimes a simpler form is used

$$E/N(eff) = \frac{E_0/N}{\sqrt{2}}$$

In Fig. 4 we show the results of our Monte Carlo simulations for the electron transport under high frequency conditions. Calculations [25], [26] were made in pure CF4 in order to provide a model of freon removal from the atmosphere by focused powerful radar beams [27]. In most of the models existence of the plasma is assumed and only the special properties related to the altitude are calculated [28]. Yet in our opinion the critical issue will be whether it is possible to achieve the breakdown and how the fields have to be focused and at which power or frequency in order to be able to produce the plasma. Major perturbations of the ionosphere such as the HARP Project fall into a different category but the question of the ionization kinetics under these circumstances still remain. Using $CF_4$ instead of air does not change any of the conclusions as the general behaviour will be similar though the actual values of the coefficients may be different. The field used in this particular calculation was $E(t)/N = 200\sqrt{2}\cos(2\pi f t) Td$.

It has been established that at high frequencies the high-energy tail of the distribution function drops down very rapidly. Thus the processes with high-energy threshold diminish while the low threshold processes are not affected by the increasing frequency. The most critical is the ionization that is affected more than other processes, but dissociation via an electronic excitation (a critical process in freon removal) also has a high threshold and shows similar behaviour. Most models that do not take into account the frequency dependent term in the calculation of the effective field will fail badly above few MHz (see Fig. 5) as they will predict constant coefficients for all frequencies. The effective field as given in Eq. 1 gives however reasonably good results and may be used if the overall ionization balance is calculated except of course at low frequencies. The good performance of the effective field theory as given by Eq. 1 is of course not guaranteed and should be checked for the actual conditions when it is to be applied.

Yet even if the overall, (time averaged) rate coefficient may be right the effective field theory cannot predict temporal developments that may result at high frequencies. Thus we have to follow the transients of the transport and rate coefficients since some special phenomena may occur that cannot be predicted on the basis of effective DC or instantaneous field theories.

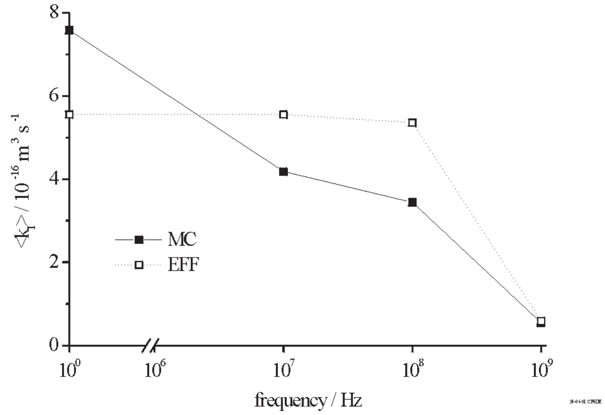


*Fig. 5. The frequency dependence of time averaged ionization rate coefficient for 1 Torr discharge in $CF_4$.*

### 4.2. Electron transport in crossed E(t)×B(t) fields

In particular, effective field theories fail when there are significant mismatches between the relaxation times for momentum and energy of electrons. These situations lead to kinetic phenomena such as anomalous diffusion [28] and time dependent negative differential conductivity [29]. We are particularly interested in behaviour for time dependent crossed field that may describe the passage of electromagnetic waves through ionized medium [30].

We have performed a Monte Carlo simulation appropriate for time changing fields (i.e. the standard null-collision technique has been replaced by numerical solution to the integral equation for the scattering probability) [23].

One example of unexpected time dependent kinetic behaviour may be observed in Fig.6. For these calculations we use the standard Reid's ramp model The longitudinal diffusion (E component) and the perpendicular component ($E \times B$) peak at times when they should, just like the transverse diffusion (the $B$ component), have a minimum. This is an effect of anomalous diffusion [21], [22] which is particular to rapidly varying electric fields and cannot be predicted on the basis of DC theories.

It is interesting to note that for purely electric field the perpendicular ($E \times B$ direction when there is magnetic field) component behaves in exactly the same way as the B component. In other words the acceleration in $E \times B$ direction is equivalent to electric field in producing the anisotropy in the diffusion tensor.

Very interesting developments of the time dependence are observed for drift velocities. The phenomena include negative differential conductivity [29], [30], asymmetric time dependence of the perpendicular ($E \times B$) drift velocity [32] which develops triangular time dependence at the highest fields and at the same time the mean drift velocity in this direction is non-zero and may even become larger than the maximum peak-to peak values of the variable component.

These studies were performed to provide the basis for improving the models for non-equilibrium plasmas such as the inductively coupled devices (ICP) and other techniques used for integrated circuit production. Under the conditions of ICP the appropriate phase between the electric and the magnetic fields is close to $\pi/2$. However for wave propagation in ionized medium more appropriate would be to use the zero phase and we have performed those calculations as well.

Dependence of the drift velocities on the phase between the two fields is shown in Fig. 7 for Reid's ramp model and for the $E/N$ value of 14.14 Td and $B/N$ value of 200 Hx at 50 MHz. The unexpected aspects of these results are, as mentioned before, the gradual change of the mean value of the ExB component and the significant change in the shape of the time dependence of the axial component ($E$). These results clearly show that standard plasma models do not take into account effects such as the phase difference between the two fields and that detailed kinetic modeling is required.

Temporal non-locality has not been taken into account by most plasma

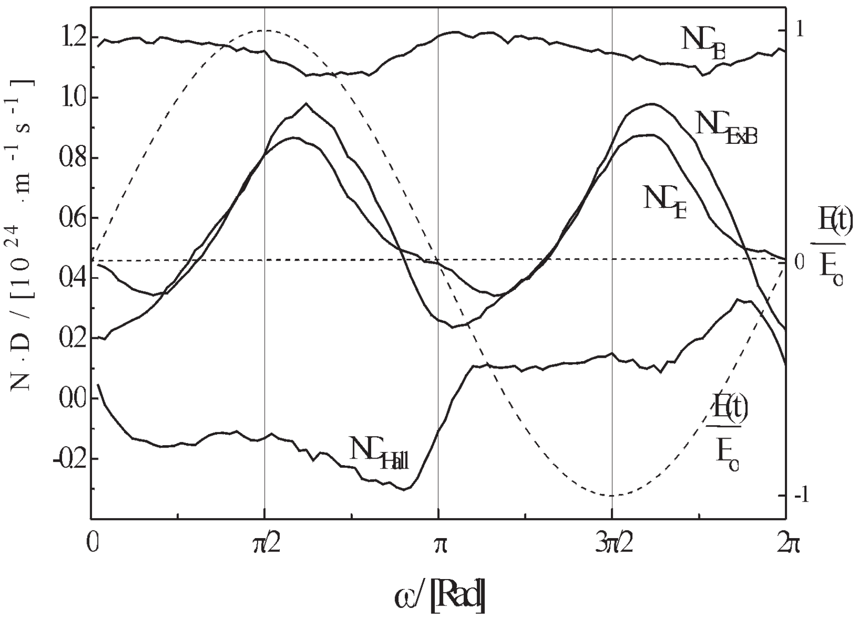
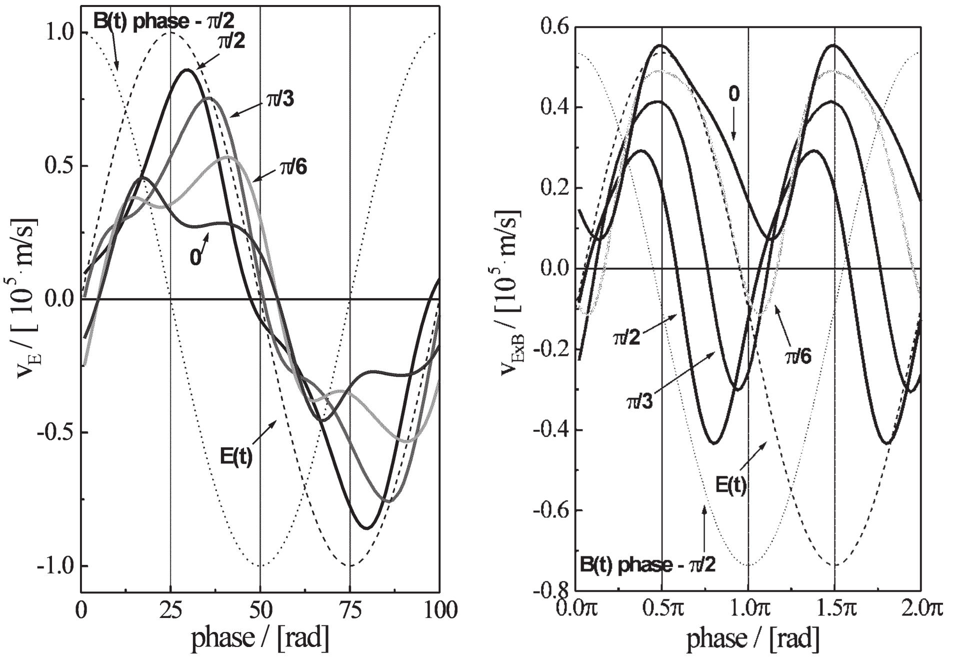


*Fig. 6. Time dependence for the components of the diffusion tensor in rf field: (E/N=14.14 Td, B/N=200 Hx 50 MHz, p=1 Torr, 1 000 000 electrons followed) subscripts show the axis based on directions of the fields. Hall diffusion coefficient describes flux of particles along one direction due to the gradient in the perpendicular direction and due to the effect of the magnetic field.. Magnetic field is a cosine function in this graph (90° shifted as compared to the electric field), which corresponds to the fields in inductively coupled plasmas (ICP) which are used for production of integrated circuits [31].*

models as the emphasis was mostly placed on spatial non-locality. The temporal effects directly affect approximate techniques involved in plasma modeling such as the relaxation continuum approximation [33], [34]. Kinetics of electrons is certainly the critical aspect of the plasma models as it occurs on the fastest time scale and also as it shows the strongest non-hydrodynamic (non-local) effects. Thus it is of key importance to test the calculation of electron transport as used by the plasma models on examples developed within the framework of swarm physics such as the examples shown above and elsewhere [23], [28]-[30]. This should also include the models of wave propagation through collisional plasmas, generation of atmospheric discharges by focused microwaves [26], [27] or by atmospheric discharges and most of all the models for non-equilibri circuit production.



(a) (b)

*Fig. 7. Time dependence for drift velocities in rf fields as a function of phase between the two fields (E/N=14.14 Td, B/N=200 Hx, ω =50 MHz, p=1 Torr, 1 000 000 electrons followed). Subscripts show the axis based on directions of the fields: (a) component (E) along electric field; (b) component perpendicular to both fields (ExB) [32].*

## 5. Plasmas in Integrated Circuit Production

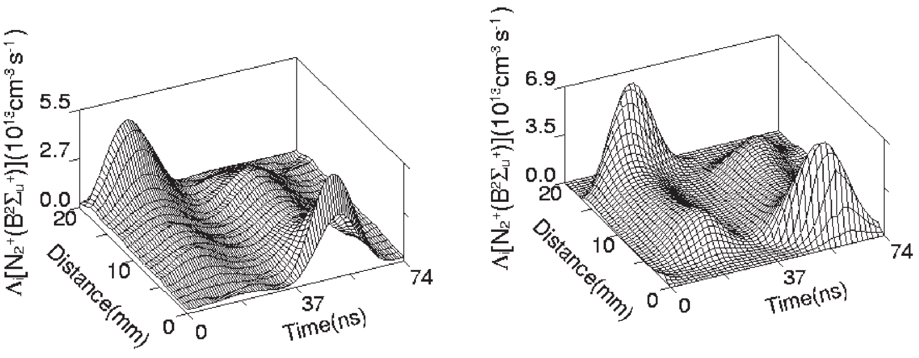
The explosive growth of telecommunication technologies has been supported mainly by the availability and the already well developed growth of the processing power and integrated circuit memories. This is partly evidenced in the choice of recipients of the Nobel prize for physics for the year 2000.

In the last twenty years plasma processing, together with photolitography, has been the dominant technology in achieving further miniaturization in integrated circuit technologies. The recent advances in ultra large scale integrated (ULSI) or submicron technologies have enabled major advances in telecommunications. The application of plasmas in integrated circuit production started through empirical developments. Recently however, the cost of a single processing devices has risen dramatically while the requirements have increased even more. Consequently the empirical development is being replaced by a combination of plasma models and well defined experiments used to verify them [32]-[35]. The models have become very accurate and reliable and are now able to predict most of the features in simpler laboratory devices that now resemble more and more the actual plasma devices. One such example is shown in Fig. 8 where we show comparison between a fluid model corrected for non-local transport by applying relaxation continuum theory [33] and the experiment measuring spatially and temporally resolved emission of a capacitively coupled plasma (CCP) in SF6 and at 50 mTorr, supplied by 13.56 MHz power. Excellent agreement that was achieved in this paper is a very good sign that our models have more realistic assumptions and are more and more successful but also it is not universal and modeling sometimes fails in special circumstances, for example due to lack of information for dissociated species. Plasma processing community hopes that in the near future further developments will occur which will allow accurate predictive modeling of complex industrial devices required to develop the computer aided design [37]-[39] and control of plasma technology. In other words day to day operation of the next generation of plasma devices will involve state of the art plasma models to be on line in the technological process.

Apart from achieving exact representation of the rf plasma reactors with complex geometries, field distributions and plasma chemistries, there are problems in plasma application that limit the further miniaturization and thus need to be resolved.

The first group are the problems arising from the high aspect ratio. The effects such as micro-trenching, notching, etch stop, redeposition and other limit the achieved resolution especially in the regions of the plasma which are close to the outer perimeter, and which correspond to the largest number of processed integrated circuits. It has been postulated that surface charging at the bottom and side-walls of micro structures is the cause of some of them [40].

Ions that hit the bottom of a small hole of trench are accelerated from a very small, almost thermal energy in plasma through the sheath potential. Thus they fall at the surface at right angle and this leads to anisotropic etching as they facilitate the effect of adsorbed radicals. On the other hand electrons start from large energies and anisotropic distribution in the bulk



(a) (b)

*Fig. 8. Spatio-temporal profiles of net excitation rate for 50 mTorr $SF_6$ capacitively coupled plasma supplied by 13. 56 MHz rf power with an amplitude of 100 V: (a) experiment, (b) plasma model [33].*

plasma and they are slowed down by the sheath potential resulting in predominant accumulation of negative charge on the top of the side-walls. Such potential distribution makes it difficult for directed electrons to reach the bottom of the high aspect ratio structures unless very high electron energies from an independent source are used. Pulsing was shown to be a possible technique to allow negative ions to reach the bottom of the micro-structures during the afterglow period after the sheath potential has collapsed.

Another group of problems occur due to the requirement to increase the size of the wafers that are being processed and currently the transition to wafer 300 mm in diameter is being finalized with pressures to go even further, to 450 and 500 mm in the next ten years. At the same time the requirements for plasma uniformity are very strict and difficult to meet on such large areas. Thus advances of the diagnostic techniques that would be able to monitor the uniformity of the plasma during the processing are required as well as the techniques to extend the uniformity of plasma over large areas. The latter is achieved by using complex antennas in inductively coupled plasma (ICP) systems. However, the models and the diagnostic techniques have to be refined on simpler geometries such as the single turn coil ICP where it is possible to obtain more directly the main sustaining mechanisms and their kinetics [41]-[43].

Finally plasma physics has to consider requirements for the further advances in plasma chemistry and plasma surface interactions that would meet the new generation of plasma tools. In addition such requirements are always posed for any new area of application and very similar plasma devices have been used in such diverse technologies as wool and polymer surface treatment for improving wettability, polymerization of surfaces, removal of polutants such as NOx and SOx from the exhaust gases, light sources, plasma displays and thin film deposition. The last application may actually be of the most immediate interest for applications in telecommunications. While other techniques offer better control and some other advantages, plasma offers a compact, dry technology that may provide a number of processes in a single reactor, from surface cleaning to deposition, ashing and etching. In Fig. 9 we show one example of a plasma deposited thin film of diamond like amorphous carbon [44] that was proposed as a protection of optical fibers against chemicals and penetration of humidity into the micro cracks. Another area that benefits greatly from the advances in experiments and models of rf and dc plasmas are the plasma thrusters. Their advantage over chemical rockets is that they provide a much better mass-impulse ratio than the chemical rockets and thus may extend significantly the lifetime of the satellites. While development in this field has lasted for more than 20 years the recent increase of the activity and the success in this field is directly fueled by the new techniques in experiments and modeling and by the additional data that were produced in attempts to model the rf discharges for plasma processing. Of the results presented here, the transport in ExB fields will be of the most immediate interest in this application but also the plasma modeling techniques, and data for the cross sections of heavy rare gases.

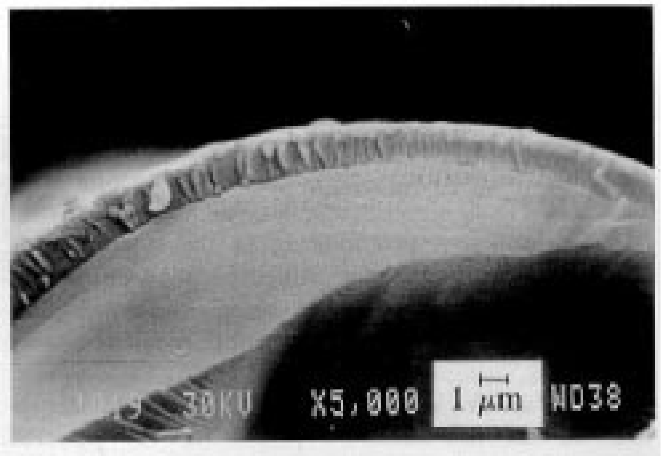


*Fig. 9. A thin film of amorphous diamond like carbon deposited on the surface of an optical fiber [44] from an rf plasma in methane.*

## 5. Conclusion

In this paper we discuss possible points of overlap between the recent advances in modeling, experiments and general understanding of phenomenology in plasma physics and the requirements associated with telecommunications. We have discussed the breakdown in the very low pressure regime due to multipacting modes, the general microwave breakdown in the atmosphere, the study of electron transport in rf fields and electromagnetic waves, plasma deposition and thrusters and most importantly the advances in plasma technologies for integrated circuit production as possible points of common interest. The connection is not as direct as in the case of integrated circuit production but integration of processing and telecommunication facilities may lead to new requirements for plasma processing. In particular it may involve combination of glass and Si based microelectronics that would lead to new problems and limitations due to charging during the processing. While new advances in plasma physics that were motivated by certain application yield a large number of new fundamental phenomena they also yield new unforeseen applications and better understanding of the available possibilities.

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