Near-surface layer formation in the surface dielectric barrier discharge driven by negative voltage pulse

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Abstract. The reason of the near-surface layer formation in the Surface Dielectric Barrier Discharge driven by negative voltage pulse has been analysed numerically. According to calculations, the thickness of this layer is around 4µm in atmospheric pressure air; it is inversely proportional to gas density and does not depend on applied voltage value and dielectric parameters. The electric field value inside a layer depends on applied voltage and changes from 60 to 600kV/cm for negative voltage pulse amplitudes from 4.5 to 24kV.

1. Introduction
Numerical modeling of the Surface Dielectric Barrier Discharge (SDBD) evolution in atmospheric air has shown that in the case of negative voltage pulse a thin anomalous near-surface layer arises with a high electric field value [1-3]. The sign of this electric field is opposite to the sign of the undisturbed field created by electrode system, and the value of this electric field depends on applied voltage value. In atmospheric pressure air it varies from 60 to 600kV/cm for negative voltage pulse amplitudes in the range 4.5 - 24kV [2].

The indirect experimental confirmation of such a layer existence was obtained in [4,5] by the measurements of radiation intensities for second positive (transition \( N_2 (C^2Π_u, ν' = 0) → N_2 (B^2Π_s, ν = 0) \), 337.1nm) and first negative (transition \( N_2 ^+ (B^2Σ^+_g, ν' = 0) → N_2 ^+ (X^2Σ^+_g, ν = 0) \), 391.7nm) nitrogen systems. Without a layer with high electric field value the radiation intensity of the first negative nitrogen system could not be so notable as recorded in experiment.

The process of the SDBD near-surface layer formation in the case of negative voltage pulse is numerically studied in this paper.

2. Numerical simulation of the SDBD evolution
Numerical simulation of the SDBD evolution was carried out using hydrodynamic 2D approach of charged particles transport equations in drift-diffusion approximation complemented by Poisson equation for the potential of self-consistent electric field. The model was described in [1,2], and its further upgrade has been delivered in [6]. The calculations were fulfilled for air at different densities \( N/N_0, 0.5N_0 \) and 0.3\( N_0 \), where \( N_0=2.7×10^{19} \text{cm}^{-3} \) is a normal density. The discharge was generated by negative voltage pulse with 8kV amplitude value and 6ns duration linear leading front. Dielectric thickness was \( d=0.2\text{mm} \), and its relative dielectric permittivity was \( ε = 5 \). Standard configuration of the SDBD is considered: a strip exposed HV electrode lays on the dielectric plate, a parallel plate grounded electrode is buried under the dielectric plate.
An example of reduced electric field $E/N$ spatial distribution for a whole discharge region at time instant $t=3\text{ns}$ is shown in figure 1. The rectangular region at the left side of the picture is the part of exposed electrode. Coordinate $x$ starts from the exposed electrode edge and comes along the dielectric surface, coordinate $y$ is in the normal direction to the dielectric surface. The electron-ion densities and electric field components distributions near discharge front in a larger scale are shown in figure 2.

Figure 1. Reduced electric field $E/N$ spatial distribution in atmospheric air $N=N_0$ at time instant $t=3\text{ns}$, when $V=-4.4\text{kV}$; $N=N_0$, $V_0=-8\text{kV}$, $d=0.2\text{mm}$, $\varepsilon = 5$

Figure 2. Colour maps of electron $n_e$ and positive ion $n_i$ densities in units of $10^{15}\text{cm}^{-3}$ (a) and electric field components $E_x$ and $E_y$ in units of $\text{kV/cm}$ (b) near the discharge front (vertical dash line); $N=N_0$, $t=3\text{ns}$, $V = -4.4\text{kV}$.

In contrast to streamer front realizing in the case of positive voltage pulse, the discharge front at negative voltage pulse does not have a sharp boundary in electron-ion density distribution. The front position denoted by vertical dash line in figure 2 is assumed to be a point of maximum longitudinal $E_x$ value in its distribution along the direction of discharge propagation (figure 3). This point corresponds
to the edge of the surface charge distribution of electrons. Thus, in contrast to positive streamer, in considered case the electric field at the front of the discharge is created not by the free volumetric charge, but by the charge of electrons attached to the dielectric surface.

![Surface charge and longitudinal electric field component distributions along the discharge propagation direction for \( t=3\text{ns}, V=-4.4\text{kV}; N=N_0 \)](image)

**Figure 3.** Surface charge and longitudinal electric field component distributions along the discharge propagation direction for \( t=3\text{ns}, V=-4.4\text{kV}; N=N_0 \)

![Calculated \( E/N \) profiles in normal to dielectric surface direction for different air densities: 1 – \( N=N_0, x=0.15\text{mm} \), 2 – \( N=0.5N_0, x=0.3\text{mm} \), 3 – \( N=0.3N_0, x=0.45\text{mm} \); solid line \(- t=6\text{ns}\), dash line \(- t=12\text{ns}\).](image)

**Figure 4.** Calculated \( E/N \) profiles in normal to dielectric surface direction for different air densities: 1 – \( N=N_0, x=0.15\text{mm} \), 2 – \( N=0.5N_0, x=0.3\text{mm} \), 3 – \( N=0.3N_0, x=0.45\text{mm} \); solid line \(- t=6\text{ns}\), dash line \(- t=12\text{ns}\).

Near-surface layer with a thickness approximately equal to 0.004mm and a peak electric field \( E_y \approx 130\text{ kV/cm} \) (\( E/N \approx 500\text{Td} \)) is well seen in figures 1 and 2. This field is approximately 4 times greater than the threshold field for ionization in atmospheric air.

The dynamics of discharge channel formation has been simulated and analyzed for different negative voltage pulses with amplitudes from -5 to -24 kV and different dielectric thicknesses in the range 0.2-1mm. In all these cases in atmospheric air we get a layer of approximately the same
thickness $\delta$=0.004 mm. The same thickness of the near surface layer in the case of negative polarity voltage has been obtained in numerical simulation [3].

The performed calculations for different pressures in the range 0.3–1atm at constant temperature $T$=300K have shown that near-surface layer thickness practically does not change during the discharge evolution (solid and dash curves in figure 4) and it is inversely proportional to gas density $N$. The results are shown in figure 4. In figure 4, for different density $N$ values the similar discharge cross sections are located at different $x$ values, which are inversely proportional to $N$. For constant $y$ value inside a layer ($y < \delta$) the $E/N$ is proportional to $1/N^2$, accordingly, $E_y \sim 1/N$. Inside a discharge channel, for $y > \delta$, the $E/N$ is constant, does not depend on gas density and approximately equal to 150Td. Thus, the electric field inside a channel is proportional to $N$. This numerical result coincides with analytical estimation [7].

3. Dynamics of near-surface layer formation

Test simulation of near-surface layer formation has been fulfilled for a case of stepwise voltage pulse $V_0 = -5$ kV and dielectric barrier with $d=0.2$mm and $\varepsilon=5$. The results are shown in figure 5.

![Figure 5](image_url)

**Figure 5.** Dynamics of spatial distributions of $n_e$ in units of $10^{15}$ cm$^{-3}$ (a) and $E/N$ in units of Td (b); $t = 0.03, 0.055, 0.06, 0.065, 0.07$ and $0.075$ns; $N=N_0, V_0 = -5$ kV, $d = 0.2$ mm, $\varepsilon = 5$

For a first shown time instant $t = 0.03$ns, corresponding to initial plasma cloud formation, the electron-ion density is too small to change the electric field of the system of electrodes. In a time, the electron-ion density inside a cloud rises up ($t=0.05–0.055$ns), but the position of the cloud practically does not change; the peak of electron-ion density is located approximately at the same point distant from the dielectric surface on 0.004mm and slowly moves in $x$ direction. For a time instant $t=0.055$ns, the initial electric field of the electrode system is already sufficiently disturbed by the spatial charge of
the cloud, but the discharge channel has not still started to form. This process begins at \( t = 0.06 \text{ns} \), when the surface charge on the dielectric surface becomes high enough and creates a high over-threshold electric field. The value of the surface charge is a key reason of the over-threshold electric field at the discharge front, which starts the formation of discharge channel. Before the beginning of channel formation, the maximum electron density is located at a distance 0.004mm above the dielectric surface. Exactly this distance later transforms into near-surface layer thickness because these electrons are accelerated and ionize gas in the electric field of the discharge front.

Consider the process of initial plasma cloud formation when the electric field is not disturbed by the spatial charge yet. The boundary condition for electron flux near the dielectric surface has a form of equality of hydrodynamic flux in drift-diffusion approach and its kinetic expression on the electron mean free path \( \lambda \) distance from the dielectric surface \([8,1,2]\)

\[
-K_e n_e E_y - \frac{\partial(n_e \lambda)}{\partial y} = -a(E_y) \frac{n_e V_T}{4} + f_{\text{out}}, \quad f_{\text{out}} = -\gamma_s I_{ly}.
\]

\[
a(E_y) = \begin{cases} 
(1 - r) \exp\left(\frac{eE_y \lambda}{T_e}\right) & \text{for } E_y < 0 \\
(1 - r) \left[\exp\left(-\frac{eE_y \lambda}{T_e}\right) + 4\left(1 - \exp\left(-\frac{eE_y \lambda}{T_e}\right)\right)\right] & \text{for } E_y > 0 
\end{cases}
\]

Here \( V_T \) – electron thermal velocity, \( a(E_y) \) is a factor describing the electron thermal flux variation due to \( E \)-field action, \( r \) – is the coefficient of electron reflection from the surface (\( r = 0 \) is assumed in current calculations), \( f_{\text{out}} \) is a flux of electrons from the dielectric surface due to secondary emission (it is equal to zero in our consideration). The quantity \( a(E_y) \) is of the order of 1, thus, a strong thermal electron flux onto the dielectric surface exists, which by definition is much greater than drift and more so diffusion fluxes. The electron density inside a part of the cloud adjacent to dielectric surface decreases due to this thermal flux, and the electron density maximum becomes shifted above the dielectric surface on a distance \( \delta \). Without thermal electron flux the maximum of electron-ion density would be on the dielectric surface because of electron-ion breeding in electron avalanches moving from the exposed electrode to the dielectric surface. Such an incorrect electron-ion distribution near the dielectric surface is observed in computations using simplified boundary conditions for electrons on the dielectric surface, as discussed in the review \([2]\). Thus, the distance \( \delta \) is a distance on which the electron-ion breeding in gas ionization process is reduced due to decrease of electron density. The scale of this distance is defined by Townsend coefficient in undisturbed electric field of the electrode system, i.e. in confirmation of our numerical results one should expect \( \delta \sim 1/N \).

To find out the \( \delta \) dependence on \( E/N \) in the undisturbed \( E \)-field of electrodes, a set of simulations has been carried out for initial plasma cloud formation at \( V = -5 \text{kV} \) and different values of the dielectric barrier thickness varying the quantity and spatial distribution of the initial electric field. It turned out, the \( \delta \) remains practically the same and equal to 0.004mm in atmospheric pressure air. Accordingly, the near-surface layer thickness is managed by gas density and gas ionization properties (Townsend coefficient) and does not depend on applied voltage value and dielectric barrier parameters.

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References

[1] Soloviev V R, Krivtsov V M 2009 J. Phys. D: Appl. Phys 42 125208
[2] Soloviev V R, Krivtsov V M 2018 Plasma Sources Sci. Technol. 27 114001
[3] Babaeva N Yu, Tereshonok D V, Naidis G V 2016 Plasma Sources Sci. Technol. 25 044008, Babaeva N Yu privat communication
[4] Nudnova M M, Aleksandrov N L and Starikovskii A Yu 2010 Plasma Phys. Rep. 36 90
[5] Stepanyan S A, Soloviev V R, Starikovskaia S M 2014 J. Phys. D: Appl. Phys. 47 485201
[6] Soloviev V R, Anokhin E M, Aleksandrov N L 2020 Plasma Sources Sci. Technol. 29 035006
[7] Soloviev V R 2019 Plasma Physics Rep. 45 264
[8] Hagelaar G J M, De Hoog F J, Kroesen G M W 2000 Phys. Rev. E 62 1452-1454