Ultraviolet (UV) emissions from a unipolar submicrosecond pulsed dielectric barrier discharge (DBD) in He-Air mixtures

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Abstract. The ultraviolet (UV) emission from a fast-pulsed dielectric barrier discharge (DBD) in a He-air gas mixture has been investigated for a wide range of operating conditions (discharge gap: 1 cm, pressure: 100 - 750 Torr, voltage: 2.5 – 8 kV, sawtooth pulse: decay time ~ 10 ns, frequency: 1.5 – 23 kHz, He-air mixture with 3%-30% air). The short-pulse excitation scheme allows the release of the charges deposited on the dielectric surfaces. The discharge (~ 10 ns) studied here is ignited only when a fast shortening pulse is applied to a previously charged electrode. The emphasis of the studies was on the UV emissions from NO, OH, N₂, and N₂⁺ between 200 nm and 400 nm and their dependence on the discharge operating parameters. It was found that the main factor that determines the spectral distribution is the amount of air admixed to the He. Because of the importance of UV emissions around 250 nm in sterilization and biological applications, a calibrated photodiode was used for absolute intensity measurements of the NO γ-band system in the 200 – 280 nm range

1. Introduction

DBDs are among the simplest discharge plasma systems, where the non-equilibrium plasma that can be generated and maintained at atmospheric pressure [1]. One of the advantages of the DBD concept is the wide range of external parameters in which a DBD can be operated such as i) geometric arrangement (parallel plate configuration, cylindrical configuration, co-planar electrode arrangements, gap spacing, etc.), ii) excitation wave forms (AC from essentially line frequency to the MHz range, pulsed DC), iii) operating gas (rare gases and rare gases admixed with molecular gases such as H₂, N₂, O₂, air, or halogens, pure molecular gases such as N₂, O₂, H₂ and gas mixtures including air and air admixed with processing gases such as silane, methane, Si-organics, etc.), and iv) operating pressure (from a few Torr to atmospheric pressure). Plasma parameters (electron energy distribution function, density of electrons and reactive species) of DBDs can be influenced and thus controlled and optimized by varying the external parameters of the discharge [2].
Recently, Liu and Neiger [3, 4], Carman and Mildren [5], and Laroussi et al. [6-8] reported the experimentally determined properties of DBDs in noble gases excited by unipolar submicrosecond square pulses. In those plasma systems a second discharge occurs at the falling edge of the voltage pulse. The sharp falling edges of the excitation pulse release the charges deposited on the dielectric surfaces by the primary discharge at the rising edge of the pulse. Bletzinger and Ganguly [9-11] suggested to excite a DBD by a slow rising and fast falling voltage pulse. The peculiarity of such a DBD is that the discharge is ignited only during the rapid drop of the applied voltage (‘step-down voltage’ DBD). The main advantage of a fast excitation is that the diffuse phase of the discharge extends to wider range of operating parameters.

The generation of a homogenous discharge is very important for germ reduction, decontamination, and biological applications. The comparatively low breakdown voltage of a discharge in helium and the ability to operate it in a uniform mode at atmospheric pressures makes such discharges attractive for industrial applications [12-15] and basic research [16-25].

Great progress has been made in understanding the key reaction mechanisms in a He discharge with admixtures of air. The primary reactions in an atmospheric-pressure He plasma are the excitation and ionization of ground state He atoms by electron impact and by collisions with excited He atoms. Molecular He ions are generated by collisions of excited He atoms [26] or ternary collisions of He atomic ions with He atoms [20]. Excited molecular nitrogen ions appear as the result of collisions of neutral N₂ and He metastables (Penning ionization) with a threshold energy of 19.8 eV, which is close to the energy of He metastables. Resonant charge transfer reactions between N₂ and He²⁺ have to be taken into account as well [19]. N₂ molecules are excited by primarily as inferred from the fact that the time dependences of the N₂ emissions follows the current pulse [19, 20]. The formation of neutral excited nitrogen molecules in collisions of metastable nitrogen molecules is discussed also in [18]. Metastable nitrogen molecules may also be responsible for the generation of OH radicals by wall reactions with adsorbed water molecules [18]. The formation of NO is the result of reactions of metastable N₂ molecules with ozone and of reactions of nitrogen atoms with oxygen atoms or OH radicals [27]. The excitation of these species by collisions of metastable nitrogen molecules are characterized by large reaction rates in the range 10⁻¹⁰ cm³ s⁻¹ [18].

Here we report the results of studies of the UV emissions from a DBD introduced by Bletzinger and Ganguly [9] in a He-air gas mixture, which is known to emit radiation attributed to NO, OH, N₂, and N₂⁺ in the range 200 – 400 nm. We investigated the variations of the emission intensities in a wide range of discharge operating parameters. In the case of the NO emissions between 200 nm and 280 nm, we also determined absolute emission intensities using a calibrated photodiode because of the germicidal effect of these emissions [28].

2. Experimental Apparatus

A schematic diagram of the experimental set up is shown in figure 1. Two 1.5 x 2 cm Cu electrodes are placed on the outside of a rectangular glass tube leaving a roughly 1 cm gap for the DBD discharge. The electrodes were charged by a DC power supply (DEL Electronics Corp Model 25RHPT10-1). A fast high-voltage switch (Behlke HTS 150) is used to apply shorting pulses and generate a submicrosecond decay of the voltage. During this voltage drop the Bletzinger and Ganguly [9] discharge is produced. The switch is triggered by rectangular pulses from a pulse generator (Tektronix CFG250). A two-stage rotary pump was used to evacuate the discharge vessel and to help maintain a stable operating pressure and gas flow in conjunction with inlet and outlet valves. Inlet needle valves between the flow meters and the discharge tube ensured that the flow meters are kept at a slightly positive pressure (relative to atmospheric pressure) during the experiments in order to minimize air leakage into the system. The discharge was operating in the following range of parameters, pressure: 100 - 750 Torr, voltage: 2.5-7.5 kV, pulse repetition rate: 1.5 – 23 kHz, He flow rate: 400-800 sccm, and air admixture: 3 – 30 %.

Optical emissions were recorded through a MgF₂ window on the side of the discharge tube, see figure 1. Quartz windows on both ends of the discharge tube allowed the visual inspection of the
discharge in a direction perpendicular to the principal optical axis. Relative intensity measurements were carried out using a 0.75 m monochromator (Jobin Yvon (JY) Horiba) conjunction with a photomultiplier tube (PMT JY 1424M). The entrance slit of the monochromator was at a distance of 28 cm from MgF₂ window and no additional optical elements were inserted between the discharge and the monochromator.

Figure 1. Schematic diagram of the experimental set-up for the absolute optical intensity measurements. For the relative intensity measurements, the photodiode was replaced by a monochromator/photomultiplier detection system (see text).

Absolute optical intensity measurements were performed with an AXUV-1000 calibrated Si photodiode (surface area 1 cm²). Figure 1 shows the experimental set-up with the photodiode. The photodiode output was recorded by an oscilloscope (with a 50 Ω impedance and a 20 MHz filter). In order to minimize inductively coupled noise caused by the fast high-voltage pulses, a Ni alloy shield and a special Cu holder for the photodiode were constructed. See also additional remarks in section 6.

3. Discharge appearance
Visual inspection of the plasma revealed a homogeneous glow (under all operating conditions) filling essentially the entire gap between the dielectric-covered electrodes. Discharges in pure He appeared with a pinkish color. A small air or N₂ admixture changed the color immediately to blue. A pinkish color of the plasma was used as a visual indicator of a system “free of air leaks” that had been evacuated to a sufficiently low pressure prior to backfilling the tube with He.

Pictures of the discharge in He with a 3.5% air admixture are shown in figure 2 for two applied voltages, 7.5 kV and 2.5 kV. The pictures were taken in a direction perpendicular to the optical analysis performed with the spectrometer. The grounded electrode is on the top of the discharge tube and the high voltage electrode is on the bottom. The appearance of the discharge is similar to that of a “secondary” discharge in Xe [4]. These “secondary” Xe discharges look more diffuse compared to “primary” discharges.

It was very difficult to observe a filamentary mode in the present work. For a very narrow range of experimental conditions (high air flow, high pressure and low voltage) the plasma shrinks to a one or two relatively stable narrow channels, which are similar to “secondary” discharges in Xe [4] at the minimum sustaining voltage. A small variation of the experimental conditions drives the discharge back to the homogeneous mode or extinguishes it.

Pictures, similar to that shown in figure 2, were used to determine a dependence of the length of the plasma in the middle of the discharge on the operating conditions. The results are shown in figure 3 with error bars representing the uncertainty in the length determination caused by the diffuse edges of the plasma. One may see that plasma length starts quickly grow with applied voltage and then slowly
approaches to electrode width. This finding is probably related to the increase of the charges that accumulate on the dielectric surface with increasing applied voltage. Dependence on pressure is nearly linear. At higher pressures plasma edges becomes sharper, at low pressure plasma expanding over electrode area. This is probably related to variation of the mean free pass of the metastable species with the pressure.

**Figure 2.** Photographs of the He discharge with 3.5% of Air: a) 7.5 kV, b) 2.5 kV. The grounded electrode is on the top.

4. General Features of the Emission Spectrum

Emission spectra of the DBD in helium are characterized by rather weak He lines (the 706.5 nm usually is the most intense line) and pronounced emissions from nitrogen impurities [7, 14-18, 25], which are difficult to avoid. In “pure” helium discharges, the $N_2^+$ band system is usually the strongest feature [14-16, 24] or at least well detectable [25], whereas the $N_2$ bands are the most intense emissions in mixtures of He and a small amount of air or nitrogen [7, 17, 18]. In [15] and [17], the authors reported a difference in the observed spectra depending on the mode of the DBD, filamentary or homogeneous. In the homogeneous mode, the emission intensity is high and additional emissions appear, which have been attributed to OH, CO+, and CO2 species [15]. Additional, but unidentified, emissions were reported in [17]. These were most likely NO emissions, which are normally present in...
He-N₂ mixtures [7, 18] and were also observed in the present work in He-air mixtures (see figure 4 below).

The presence of emissions assigned to impurities in the spectrum of a “pure” He discharge is caused by small air leaks in the vacuum system and the residual presence of moisture (H₂O) in the plasma reactor. Evacuation of the plasma reactor to pressures of 10⁻³ Torr before backfilling it with He to pressures above 100 Torr might still result in very strong nitrogen, oxygen, hydrogen, and OH emissions [15]. In work [25] it was possible to reach conditions when the He line 706.5 nm is the strongest spectroscopic feature. The vacuum chamber in [25] was evacuated better than 0.1 Torr but in contrast to [15] it was not needed to open vacuum chamber in order to insert samples.

![Typical UV spectrum emitted by our DBD discharge in He-air mixtures.](image)

**Figure 4.** Typical UV spectrum emitted by our DBD discharge in He-air mixtures. a) overview spectrum; b) – e) spectral regions of interest: b) NO (1,0) γ-band at 236 nm, c) OH A ²Σ⁺ → X ²Π (0,0) band between 306 and 312 nm with the Q1(3) and Q21(3) lines marked, d) (0,0) band of the N₂⁺ 1ˢᵗ negative system near 391 nm, and e) (1,0) band of the N₂ 2ⁿᵈ positive system near 357 nm.
High-pressure discharges in noble gases provide an environment that is conducive to an efficient excitation of impurities via e.g. energy transfer processes involving energetic metastables and excimers [29, 30]. In [21] was noted that the presence of impurity in He discharges plays an important role in the modeling of DBDs in He.

In the present work, we focused our studies on the UV part (200-400 nm) of the emission spectrum of a fast-pulsed DBD in high-pressure He and He-air mixtures, see figure 4. The emission spectra are dominated by the N2 second positive system and the N2⁺ first negative system and are generally similar to those reported earlier by other groups for homogeneous DBD discharges in He and He-N2 and He-air mixtures. In our studies we observed NO emissions in discharges in He-N2 and He-air mixtures, but not in "pure" He DBDs and weak emissions attributed to OH in all spectra.

The slit widths of the monochromator were chosen for every emission separately in order to avoid saturation of the photomultiplier tube (PMT) while achieving the highest signal-to-noise ratio. We note that the recorded N2 emissions were found to saturate the PMT at much lower time-averaged intensities compared to the NO and OH emissions. This is probably the result of the fast-pulse excitation and the resulting fast-pulsed N2 emission in conjunction with the fact that the PMT only records time-averaged optical emission intensities. The N2 emissions follow directly the fast excitation pulse and a short, very intense N2 emission pulse can easily saturate the PMT. On the other hand, the NO and OH emissions are the result of plasma chemical reactions following the fast-pulse excitation. Their emission, even if intense, is spread out over a much longer time scale, and thus may not saturate the PMT. Time-resolved measurements reported in [20] and [25] also showed a delay of the OH emission relative to the N2 (and N2⁺) emission.

Figure 5. Relative intensity of the NO, OH, N2⁺ and N2 emissions as a function of the applied voltage at a) 300 Torr and at b) 500 Torr, normalized at their maximum. The pulse repetition rate is 20 kHz, the He flow rate is 400 ml/min, and the air admixture is 6.7%.

5. Dependence of the Emission Intensities on the Discharge Operating Parameters
For our investigations of the dependence of the emission intensities on the discharge parameters, one emission peak for each molecule (NO, OH, N2 and N2⁺) was selected. These four emissions are marked in figure 4a and are shown separately in figures 4b-e. We did not use the strongest N2 band at 337nm, but rather the (1,0) band at 357nm for further investigation to avoid saturation of the PMT. The measured emission intensities as a function of the various discharge operating parameters are shown in figures 5-9. In order to facilitate a convenient comparison of the various emission intensities,
each emission intensity was normalized at its maximum value. Error bars, where indicated, represent the statistical error in the data obtained from five independent measurements carried out under same experimental conditions.

Figure 5 shows the emission intensities as function of the applied voltage at two operating pressures, 300 Torr and 500 Torr for He with a 6.7% air admixture. As one can see, the intensities of all four emissions increase with voltage. The rate of increase in the emission intensity with increasing voltage is larger at the higher pressure. The observed trends did not depend on the exact air admixture. The general trend of the curves in figure 5 is expected. It is reasonable to assume that higher voltages correspond to higher power deposition into the plasma, which, in turn, leads to higher populations of the emitting levels and higher emission intensities.

Figure 6 shows the variations of the same four emission intensities as a function of the applied voltage for a 500 Torr He discharge with a 5% N₂ admixture. Here the N₂⁺ and N₂ emission intensities follow the same trend that was observed in the case of the air admixture. On the other hand, the NO and OH emission intensities now show a qualitatively different behavior with a distinct maximum at 5 kV. Therefore the presence of oxygen influences the excitation kinetics of NO and OH stronger than its for N₂ and N₂⁺.

Figure 6. Relative intensity of the NO, OH, N₂⁺ and N₂ emissions, normalized at their maximum, as a function of the applied voltage at 500 Torr. The pulse repetition rate is 20 kHz, the He flow rate is 400 ml/min with an N₂ admixture of 5%.

Figure 7 shows the emission intensities as a function of air admixture. The air admixture was calculated as a percentage of the He flow. It is apparent that all emission intensities are decreasing with increasing air admixture. The NO, OH and N₂⁺ intensities show a very pronounced non-linear dependence, while the N₂ intensity declines linearly. Unfortunately in present set up it was very difficult to control and stabilize air admixtures below 3%.
Figure 7. Relative intensity of the NO, OH, N$_2^+$ and N$_2$ emissions, normalized at their maximum, as a function of the air admixture at 300 Torr. The pulse repetition rate is 20 kHz, the He flow rate is 800 ml/min and the voltage is 7.5 kV.

The dependence of the N$_2$ emission intensity on the N$_2$ admixture measured in a He-N$_2$ DBD excited by square unipolar pulses [7] was found to exhibit a maximum at around 5-10% N$_2$. With further increasing N$_2$ concentration, the N$_2$ emission intensity slowly decreased. Those observations are qualitatively in agreement with our observations in He-air DBD, if one takes into account the change of the plasma size in our discharge in dependence on air admixture.

Figure 8 shows the emission intensities as a function of pressure. Here, the N$_2^+$ emission shows a behavior that is different from the other three emission features. Its intensity declines essentially linearly with pressure, whereas the other three emissions exhibit a bell-shaped pressure dependence with a maximum intensity around 350 Torr. The pressure-dependence of the N$_2^+$ emission intensity is rather similar to the variation of the plasma length with pressure, see figure 3b.

Figure 8. Relative intensity of the NO, OH, N$_2^+$ and N$_2$ emissions, normalized at their maximum, as a function of pressure. The voltage is 7.5 kV, the pulse repetition rate is 20 kHz, the He flow rate is 800 ml/min with an air admixture of 3.5%.
The dependencies of the $N_2$ and $N_2^+$ emission intensities as a function of pressure measured in a Ar-$N_2$ mixture in the same type of DBD [9] agree qualitatively with our findings in He-air mixtures. The $N_2$ emission intensity in the Ar-$N_2$ DBD has a similar bell-shaped dependence, but maximum occurs at a lower pressure around 100 Torr. The $N_2^+$ emission intensity shows a nearly linear decrease with pressure between 100 and 200 Torr, but at lower pressures the dependence becomes stronger than linear.

Figure 9 shows the emission intensities normalized to the pulse repetition rate, i.e. the intensity per discharge pulse as a function of the pulse repetition frequency. While the $N_2$, $N_2^+$, and OH emission intensities per pulse decline linearly with increasing repetition rate by about 25% between 1 and 20 kHz, the NO emission intensity per pulse increase by about a factor of 2 in the same range and then levels off above about 20 kHz. The decrease of $N_2$ and $N_2^+$ emission intensities with repetition frequency in the same type of DBD in an Ar-$N_2$ mixture were reported in [11]. The dependence of $N_2$ emission intensity was found to be in good agreement with the present observation, while the dependence of $N_2^+$ emission intensity reported in [11] was distinctly non-linear in contrast to the finding in the present work.

As one can see from figures 5-9, the relative intensities of the NO, OH, $N_2$ and $N_2^+$ species behave differently when the discharge operating parameters are varied. We believe that the observed dependencies reflect differences in the excitation and plasma chemical pathways that contribute to the formation and destruction of the emitting species. They can give some insight into the nature of the dominant reaction chains in high-pressure He and He-air plasmas excited by short pulses. But therefore further studies, in particular, measurement of ground state particle concentrations, time-resolved studies in conjunction with modeling and simulation are needed to shed further light on the basic processes in these plasmas.

The ability to interpret data from time- and space-averaged emission intensities from fast-pulsed DBDs and to extract meaningful conclusions is obviously very limited because invaluable time- and space-dependent information is washed out in the averaging process. During the exciting pulse the discharge develops in the direction of the electrodes [8, 15] as well as radially, the determination of spatially resolved emission intensity dependences on the discharge operating parameters is highly desirable [22] [25]. The temporal variations of the emission intensities of the different species will differ significantly from species to species depending on – among other factors – whether the emitting species is excited directly by the plasma electrons or is the result of a subsequent plasma chemical reaction chain (see discussions in [18], [20], [25]).

**Figure 9.** Relative intensity of the NO, OH, $N_2^+$ and $N_2$ emissions per pulse, normalized at their maximum, as a function of the pulse repetition rate at 300 Torr. The voltage is 7.5 kV, the He flow rate is 800 ml/min with an air admixture of 3.5%.
6. NO $\gamma$-band Emissions

The emission of NO $\gamma$-band system has been studied in more detailed due to the potential of using the NO $\gamma$-band radiation in the UV for biomedical applications. Systematic investigations similar to those results are shown in figures 5-9 for all four emission features were carried out for the NO emission system for a much wider range of operating parameters in an effort to establish operating conditions that yield maximum NO emission intensity. The results can be summarized as follows:

- The NO emission intensity as a function of applied voltage (between 3 and 8 kV) was studied for several operating pressures between 200 Torr and 500 Torr and was found to increase in all cases with increasing voltage. The increase was linear at 200 Torr, but becomes essentially quadratic at 500 Torr.

- The NO emission intensity as a function of pressure showed the same bell-shaped dependence with a pronounced maximum that was already shown earlier in figure 8. However, the pressure, at which the peak emission occurs, increases with the applied voltage from 100 Torr at 3 kV to 300 Torr at 7 kV.

- The NO emission rapidly declines as a function of air admixture for various voltages, pulse repetition frequencies, and pressures. A maximum in the emission intensity can be obtained for air admixtures below 2%. In discharges in pure He, no NO emissions have been found. Thus, intense NO emissions are obtained for high voltage pulses, intermediate pressures, and air admixtures of less than about 2%. It is worth noting that NO emissions measured in discharges in He-N$_2$ mixture are more intense by about more than an order of magnitude in comparison to discharges in He-air under comparable discharge operating conditions. In [7] it has been reported that 1% of oxygen added to He (89%) + N$_2$ (10%) mixture leads to drastic drop of NO emission. In case of 2% of air admixture the oxygen content is around 0.4%, and probably it is too high for optimum of NO emission. Unfortunately with N$_2$ admixture it was difficult to stabilize the intensity of NO emission in present experiment; it was decreasing on about one order of magnitude during 5-6 hours after discharge ignition. These facts underline the importance of gas impurity control and the requirement of the vacuum system in order to optimize the NO emission intensity in our discharge.

Subsequently, absolute intensity measurements of the NO emission were carried out using a calibrated photodiode. Because of the fast-pulsed excitation of the DBD, the measurements with the photodiode were highly susceptible to electrical noise. In order to minimize inductively coupled noise caused by the high current pulses, a Ni alloy shield and a special Cu holder for the photodiode were constructed (see figure 1). The distance between the discharge and the photodiode is an important parameter in noise considerations. The inductively coupled noise only weakly depends on the distance and becomes the dominant noise contribution at distances of 6 cm and more. On the other hand, the capacitively coupled noise increases sharply when the photodiode is close to the discharge.

The rise time of the AXUV100 photodiode is approximately 100 ns and the fall time is larger than 1 $\mu$s (which are both long compared to the roughly 10 ns pulse that excites the DBD). The response of a Si photodiode to pulsed radiation has been investigated by several authors [31-33]. A typical photodiode signal recorded by the oscilloscope is shown in figure 10 (the background has been subtracted for clarity of presentation). As one can see, the time between light pulses is sufficiently long, so that all charges from the photodiode, which were created during the light pulse, can be collected. Therefore, the time-integrated signal of the photodiode is proportional to the number of photons emitted from the plasma.

1 air flow below 3.5% was roughly estimated.
The sensitivity of the photodiode has been calibrated at NIST for the 50-250 nm spectral range. Taking into account that (i) the internal quantum efficiency is a relatively slow-varying, monotonic function of the wavelength [34] in the range of interest and (ii) silicon dioxide films create interference fringes affecting the external efficiency (sensitivity) [35], we estimate the sensitivity of the photodiode in the 200-320 nm to be constant to within ±30%.

Silicon photodiodes are sensitive to radiation of a wide range of wavelengths from the vacuum UV to the infrared [34]. In order to extract a signal from the photodiode response that corresponds only to the UV radiation attributed to the NO emissions, we employed a series edge filters with well-defined cut-off wavelengths, which absorb all wavelengths shorter than the cut-off wavelength. Specifically, we used the SCS245, SCS280 and SCS320 filters from International Light, which have a transmittance of 60% at 245 nm, 280 nm and 320 nm, respectively, as well as a glass plates with a transmittance close to that of the SCS320 filter, which was measured using a HP 8452A Diode Array Spectrophotometer. At the short wavelength end, our measurements were limited by the absorption of air, which starts around 200 nm.

The experimental procedures with the SCS filters and the glass plates were different. When the filters were used, the difference in the photodiode signals measured separately with two different filters in place was interpreted as the photodiode response to radiation in the wavelength range between the two filter edges. When the glass filters were used, the effective transmittance of the glass plates for visible light was determined as a ratio of signals with one and two glass plates in place. The estimated signal corresponding to visible light was then subtracted from the total signal measured without the glass plates. This allowed us to obtain the absolute intensity of the radiation in the wavelength range 200 – 320 nm.

Except for the air admixture, the absolute intensity measurements were performed under favorable conditions that maximize the UV emission intensity (as determined by the previously established conditions for maximum NO emissions), He flow 800 ml/min, 300 Torr, 7.5 kV, 20kHz, distance of the photodiode from MgF2 window is 6 cm. We used a 3.5% air admixture, which was easy to stabilize over long periods of operation rather than lower air admixtures, which result in more intense emissions, but were difficult to quantify and stabilize. The results are summarized in Table 1.
Table 1. Measured UV radiation by a 1 cm² silicon photodiode at a distance of 6 cm from the discharge tube at 20kHz, 300 Torr, 7.5 kV, a He flow 800 ml/min, 3.5% air admixture.

| Method          | SCS filters | Glass plates |
|-----------------|-------------|--------------|
| Wavelength range, nm | 245-280     | 280-320      | 245-320     | 200-320     |
| Intensity per pulse, pJ/cm² | 40±30      | 70±30        | 110±40      | 120±50      |
| Radiation power, µW/cm²  | 0.8±0.6    | 1.4±0.6      | 2.2±0.8     | 2±1         |

Taking into account the solid angle of observation subtended by the photodiode detector and assuming an isotropic NO emission, we estimate the total NO radiative power to be 30 µW. Based on a total power input of about 60 W (much of which is dissipated in the resistor R), we estimate a “wall-plug” efficiency for the NO emission of 5 x 10⁻⁷. While this efficiency is very low, we note that the NO emissions are weak compared to the other UV emissions (see figure 4) and that a significant fraction of the electrical input energy will be converted to He₂⁺ excimer emissions in the extreme vacuum UV (50 – 90 nm), which we could not measure in the present experiments, see [23].

7. Summary
The UV emission of fast-pulsed, step-down DBD with gap of 1 cm in He-air mixtures has been investigated for a wide range of experimental conditions, pressures of 100-750 Torr, applied voltages of 2.5 – 8 kV, air admixtures of 3% – 30 %, and pulse repetition frequencies of 1.5 – 23 kHz. Distinct differences in the variation of the emissions of NO, OH, N₂⁺, and N₂ are indicative of the different excitation routes and plasma chemical reaction pathways that lead to the formation of the various excited species. The absolute optical intensity of the NO γ–band system emission is of the order of a µW per cm² at a distance of 6 cm from a roughly 1 cm³ DBD discharge and a total input power of about 60 W. Lastly, it has been shown that (i) the amount of air admixture to the He is the most critical parameter for the optimization of the UV radiation (and we estimate that the emission intensity peaks at oxygen admixtures at or below 0.4%) and (ii) an increase in the applied voltage not only increases the UV emissions, but shifts the conditions for maximum emission intensity to higher pressures (and we estimate that an electric field of 20 kV/cm may be required in order to have the emission peak at atmospheric pressure).

A more detailed understanding of the pathways of the plasma chemical reactions is still missing. Elucidating the plasma chemistry will require reliable measurements of the concentrations of particles in the ground state in conjunction with time-resolved studies and the utilization of modeling and computer simulations.

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References
[1] Kunhardt E E 2000 Generation of large-volume, atmospheric-pressure nonequilibrium plasmas IEEE Transactions on Plasma Science 28 189-200
Kogelschatz. U, Salge J. 2001, High-pressure plasmas: dielectric-barrier and corona discharges – properties and technical applications in Hippler r, Pfau S, Schmidt M, Schoenbach K H (Eds.)Low Temperature Plasma Physics Wiley-VCH
[2] Gellert B 1991 UV-generation in dielectric barrier discharge Contr. Plasma Phys. 31 247-59
[3] Liu S and Neiger M 2001 Excitation of dielectric barrier discharges by unipolar submicrosecond square pulses J. Phys. D.: Appl. Phys. 34 1632-38
[4] Liu S and Neiger M 2003 Double discharges in unipolar-pulsed dielectric barrier discharge xenon excimer lamps J. Phys. D.: Appl. Phys. 36 1565-72
[5] Mildren R P and Carman R J 2001 Enhanced performance of a dielectric barrier discharge lamp using short-pulsed excitation J. Phys. D.: Appl. Phys. 34 L1-L6
[6] Laroussi M, Lu X, Kolobov V and Arslanbekov 2004 Power consideration in the pulsed dielectric barrier discharge at atmospheric pressure J. Appl. Phys. 96 3028-30
[7] Lu X and Laroussi M 2005 Optimization of ultraviolet emission and chemical species generation from a pulsed dielectric barrier discharge at atmospheric pressure J. Appl. Phys. 98 Art. No. 023301.
[8] Lu X P and Laroussi M 2006 Temporal and spatial emission behaviour of homogeneous dielectric barrier discharge driven by unipolar sub-microsecond square pulses J. Phys. D.: Appl. Phys. 39 1127-31
[9] Bletzinger P and Ganguly B N 2003 The effect of displacement current on fast-pulsed dielectric barrier discharges J. Phys. D.: Appl. Phys. 36 1550-52
[10] Williamson J M, Bletzinger P and Ganguly B N 2004 Gas temperature determination in a N2/Ar dielectric barrier discharge by diode-laser absorption spectroscopy and resolved plasma emission J. Phys. D.: Appl. Phys. 37 1658-63
[11] Williamson J M, Bletzinger P and Ganguly B N 2005 Absolute and relative density measurements in a N2/Ar dielectric barrier discharge by diode-laser absorption spectroscopy and resolved plasma emission J. Appl. Phys. 97 Art. No. 103301
[12] Boricia G, Dumitrascu N and Popa G 2005 Influence of helium-dielectric barrier discharge treatments on adhesion properties of polyamide-6 surface Surface and Coatings Technology 197 316-21
[13] Montie T C, Kelly-Wintemberg K and Roth J R 2000 An overview of research using the one atmosphere uniform glow discharge plasma (OAUUDP) for sterilization of surfaces and materials IEEE Transactions on Plasma Science 28 41-50
[14] Laroussi M and Lu X 2005 Room-temperature atmospheric pressure plasma plume for biomedical applications Appl. Phys. Lett. 87 113902
[15] Massines F and Gouda G 1998 A comparison of polypropylene-surface treatment by filamentary, homogeneous and glow discharges in helium at atmospheric pressure J. Phys. D.: Appl. Phys. 31 3411-20
[16] Massines F, Segur P, Gherardi N, Khamphan C and Ricard A 2003 Physics and chemistry in glow dielectric barrier discharge at atmospheric pressure: diagnostics and modeling Surface and Coatings Technology 174 8-14
[17] Chiper A S, Anita V, Aghieorghiesei C, Pohoata V, Anita M and Popa G 2004 Spectroscopic diagnostics for a DBD plasma in He/Air and He/N2 gas mixtures Plasma Process. Polym. 1 57-62
[18] Bibinov N K, Fateev A A and Wiesemann K 2001 On the influence of metastable reactions on rotational temperatures in dielectric barrier discharge in He-N2 mixtures J. Phys. D.: Appl. Phys. 34 1819-26
[19] Nersisyan G and Graham W G 2004 Characterization of a dielectric barrier discharge operating in open reactor with flowing helium Plasma Sources Sci. Technol. 13 582-7
[20] Ricard A, Decomps Ph and Massines F 1999 Kinenetics of radiative species in helium pulsed discharge at atmospheric pressure Surface and Coatings Technology 112 1-4
[21] Golubovskii Yu B, Maiorov V A, Behnke J and Behnke J F 2003 Modelling of the homogeneous barrier discharge in helium at atmospheric pressure J. Phys. D.: Appl. Phys. 36 39-49
[22] Mangolini L, Orlov K, Kortshagen U, Heberlein J and Kogelschatz U 2002 Radial structure of a low-frequency atmospheric-pressure glow discharge in helium Applied Physics Letters 80
[23] Kurunczi P, Lopez J, Shah H, Becker K 2001 Excimer formation in high-pressure microhollow cathode discharge plasmas in helium initiated by low-energy electron collisions. International Journal of Mass Spectrometry \textbf{205} 277-83

[24] Arkhipenko V I, Kiri1ov A A, Simonchik L V and Zgirouski S. M 2005 Influence of the nitrogen-helium mixture ratio on parameters of a self-sustained normal dc atmospheric pressure glow discharge. Plasma Sources Sci. Technol. \textbf{14} 757-65

[25] Navratil Z, Brandenburg R, Trunec D, Brablec A, St’ahel P, Wagner H-E and Kopecky Z 2006 Comparative study of diffuse barrier discharge in neon and helium. Plasma Sources Sci. Technol. \textbf{15} 8-17

[26] Loeb L. B., Basic Processes of Gaseous Electronics University of California Press Berkeley 1955 p79

[27] Herron J T 2001 Modeling studies of the formation and destruction of NO in pulsed barrier discharges in nitrogen and air. Plasma Chemistry and Plasma Processing, \textbf{21} 581

[28] Jewess B W 1978 Some medical uses of radiation from lamps. Lighting Research & Technology \textbf{10} 184-8

[29] Becker K H, Kurunczi P F and Schoenbach K H 2002 Collisional and radiative processes in high-pressure discharge plasmas. Physics of Plasmas \textbf{9} 2399-404

[30] Masoud N, Martus K and Becker K 2005 VUV emission from a cylindrical dielectric barrier discharge in Ar and in Ar/N$_2$ and Ar/air mixtures. J. Phys. D: Appl. Phys. \textbf{38} 1674-83

[31] Vest R E and Grantham S 2003 Response of a silicon photodiode to pulsed radiation.” Applied Optics \textbf{42} 5054-5063

[32] Korde R, Prince C, Cunningham D, Vest R E and Gullikson E 2003 Present status of radiometric quality silicon photodiodes. Metrologia \textbf{40} S145-9

[33] Stuik R and Bijkerk F 2002 Linearity of P-N junction photodiodes under pulsed irradiation. Nuclear Instruments and Methods in Physics Research A \textbf{489} 370-8

[34] Korde R and Geist J 1987 Quantum efficiency stability of silicon photodiodes. Applied Optics \textbf{26} 5284-90

[35] Canfield L R, Vest R E, Korde R, Schmidtke H and Desor R 1998 Absolute silicon photodiodes for 160 nm to 254 nm photons. Metrologia \textbf{35} 329-34