

HETEROGENEOUS SURFACE RECOMBINATION OF NEUTRAL NITROGEN ATOMS

HETEROGENA POVRŠINSKA REKOMBINACIJA DUŠIKOVIH NEVTRALNIH ATOMOV

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An overview of data reported in literature on heterogeneous surface recombination of nitrogen atoms is presented. The data are often scattered for over an order of magnitude depending on experimental technique and perhaps also on surface finish. As a general rule the recombination coefficient is rather small for materials that do not chemisorb nitrogen atoms, and it is rather large for some metals that are known as catalysts. Values as low as 5×10^{-8} have been reported for Pyrex glass, although a typical value of the recombination coefficient for glasses is rather 1×10^{-5} . The similar order of magnitude is found for very stable polymers such as polytetrafluoroethylene (teflon), although larger values are typical for some other polymers. The recombination coefficient for metals is typically 10^{-2} but can be as large as 0.3 for selected catalysts.

Keywords: nitrogen plasma, neutral nitrogen atoms, surface recombination, recombination probability

Podajamo pregled podatkov iz literature o heterogeni površinski rekombinaciji dušikovih atomov. Obstoječi podatki se pogosto razlikujejo za več kot velikostni red odvisno od eksperimentalne tehnike in verjetno tudi od predobdelave površine. V splošnem je rekombinacijski koeficient precej majhen za materiale, ki ne kemisorbirajo dušikovih atomov in precej velik za nekatere materiale, ki so znani kot katalizatorji. Zelo majhne vrednosti okoli 5×10^{-8} so bile objavljene za steklo Pyrex, čeprav je bolj značilna vrednost rekombinacijskega koeficienta za steklo okoli 1×10^{-5} . Podoben velikostni red velja tudi za polimere kot je politetrafluoroetilen (teflon), medtem ko so za ostale polimere značilne precej višje vrednosti. Rekombinacijski koeficient za kovine je tipično okoli 10^{-2} , vendar je lahko tudi precej višji okoli 0.3 za nekatere katalitične materiale.

Ključne besede: dušikova plazma, nevtralni atomi dušika, površinska rekombinacija, verjetnost za rekombinacijo

1 INTRODUCTION

Nitrogen plasma has attracted much attention in the past decades not only due to application for surface modifications of various materials¹⁻² but also due to some specific characteristics of excited particles found in non-equilibrium nitrogen plasma.³ Low pressure non-equilibrium gaseous plasma is always characterized by a rather high average energy of electrons and a rather low kinetic temperature of all other particles.⁴⁻⁶ The simplest example of such plasma is created in a noble gas. Free electrons are accelerated in an appropriate electric field, typically next to the powered electrode and enter plasma volume with a kinetic energy often exceeding 100 eV. In plasma volume they suffer from elastic collisions with slow electrons. These collisions assure for a rapid thermalization of the fast electrons: they effectively lose their kinetic energy, while plasma electrons gain it. According to the basic roles of statistical mechanics such intensive energy exchange always leads to a Maxwellian distribution of particles over their kinetic energy.

Plasma is therefore rich with electrons with a Maxwellian energy distribution function. The high energy tail of the function is exponential so the electrons may gain practically any kinetic energy well above their average kinetic energy. Number of electrons with very high kinetic energy (in the high energy tail) are capable of

ionizing any atom or molecule. In the case of noble gas such direct ionization may occur since there is a lack of low energy excited states of atoms. For instance, the first excited state of helium atom is at 20.2 eV⁷ while the ionization energy is 24.6 eV.⁸ Similar considerations apply for many other atomic plasmas, but fail completely in the case of nitrogen plasma. Namely, nitrogen plasma has some unique characteristics due to many different excited states that may or may not be metastable. The unique properties of these excited states make characterization and understanding of nitrogen plasma rather difficult, let alone interaction of such plasma with solid materials.

2 CHARACTERISTICS OF LOW-PRESSURE NON-EQUILIBRIUM NITROGEN PLASMA

Nitrogen molecules are characterized by a variety of different excited states. Most of these excited states are metastable with a typical radiative lifetime exceeding 1 ms. The dissociation energy of a nitrogen molecule is much higher than for many other molecules including oxygen, hydrogen and alike. The ionization energy is also rather high at about 14.5 eV.⁹ Some excited states of nitrogen molecules are presented in Refs. 2 and 3. The richness of excited states causes many channels for electron energy loss at inelastic collisions with nitrogen

molecules. Unlike for the case of noble gases where the channels are limited, a collision with a fast electron from a high energy tail is likely to cause excitation of such a molecule rather than dissociation or even ionization. Electrons with a lower kinetic energy are likely to excite vibrationally excited states. Nitrogen molecules are famous for many vibrational excited states. Unlike in many other gases where superelastic collisions between vibrationally excited molecules and other particles cause substantial cooling of the vibrational states, the coupling between vibrational and translational states for nitrogen molecules is extremely poor. A consequence of that is that nitrogen molecules are found in highly vibrationally excited states even in a plasma created by a weak electrical discharge.^{9,10} The high excitation energy of electronically excited states as well as rich population of vibrationally excited states of nitrogen molecules in gaseous plasma allow for interesting inelastic collisions that may lead to either dissociation or even ionization of nitrogen molecules. Such multistep processes, that involve firstly excitations by electron impact and then redistribution of the potential energy finally causing dissociation or ionization, make any predictions about the behaviour of nitrogen plasma very difficult. Until recently, not many methods have appeared for determination of the basic plasma parameters such as dissociation fraction in nonequilibrium plasma. Application of optical absorption techniques i.e. TALIF,¹¹ NO titration,¹² and catalytic probes^{13,14} definitely help understanding interaction between nitrogen plasma and solid materials.

Reactive particles of particular importance are neutral nitrogen atoms in the ground state. In nitrogen plasma they are usually found at the kinetic temperature close to the temperature of plasma facing components. In many technologically important nitrogen plasmas they actually represent the most important reactants. The interaction between neutral nitrogen atoms and solid materials can be either chemical or physical. Chemical interaction stands for a chemical reaction between a nitrogen atom and a solid material atom. Nitrogen atoms can either bond onto the surface forming a sort of a nitride, or pick an atom from the surface forming a radical that can leave the surface. A typical example of the latter mechanism is etching of organic materials or hydrogenated carbon by neutral nitrogen atoms.¹⁵

The consequence of the chemical reactions is a loss of neutral nitrogen atoms. The loss rate definitely depends on the intensity of the chemical reactions. In many practical cases however, chemical reactions are not predominant mechanism of neutral nitrogen atom loss. In many cases, the major mechanism is a physical reaction which is often called heterogeneous surface recombination. Nitrogen atoms are chemically rather reactive and can chemisorb on surfaces of different materials. If such chemisorption occurs, another atom from the gas phase may adsorb on the same site. The abundance of chemisorbed atoms can quickly cause formation of a molecule

which does not fill strong chemisorption bonds but is rather desorbed from the surface immediately after being formed. This is so called Eley-Rideal mechanism of heterogeneous surface recombination. The other mechanism is the so called Langmuir-Hinshelwood which postpones surface migration of nitrogen atoms until they found a suitable site where they recombine and leave the surface of the solid material as a molecule. Whatever the mechanism is the recombination probability is often expressed in the terms of recombination coefficient which has been defined as the ratio between the number of atoms recombining on a surface area in a unit time and the total flux of atoms on the surface from the gas phase. Since the loss of atoms by a surface recombination is often the most important mechanism for draining atoms from plasma many authors attempted to measure it.

3 SELECTED RESULTS FOR NITROGEN ATOM RECOMBINATION COEFFICIENTS

The literature on recombination of neutral nitrogen atoms is scattered among different journals and also different periods. The techniques used for quantification of the recombination probabilities heavily depend on a sort of model predicting the behaviour of atoms near a surface. As mentioned earlier nitrogen atoms are usually not produced by direct impact dissociation of a molecule in a ground state but also at other collisions. In practice it means that the atoms can be also produced away from glowing discharge in the region called an afterglow. In fact, measurements in the discharge itself are usually too complicated and often not very reliable so the majority of recombination coefficients was measured under afterglow conditions.

The recombination coefficients for two types of glasses often used in construction of vacuum systems as well as plasma reactors are presented in **Table 1**. A quick look at the **Table 1** reveals that the recombination coefficient is very low. This means that nitrogen atoms practically do not interact with glasses. The explanation has been given implicitly in the upper text and will be only stressed again here. The lack of chemisorption states on chemically very inert glasses prevent substantial sticking of nitrogen atoms on the surface so the probability of recombination is extremely low. A detailed consideration of **Table 1** indicates a rather large scattering of the experimental results. The smallest value of 5×10^{-8} was found by Brennenen¹⁶ while on the other hand Gordiets¹⁷ reported values of the order of 10^{-4} and even larger for a more complex experiment. The discrepancy of the results is therefore over four orders of magnitude and may be explained by particularities of the experimental set-ups, surface finish of the materials and possibly also the purity of materials used at particular experiment.

Table 1: Recombination coefficients for borosilicate glass (Pyrex) and quartz glass as obtained by different authors

Tabela 1: Rekombinacijski koeficienti za borosilikatno steklo (Pyrex) in kvarčno steklo

Reference	Material	Recombination coefficient	Temperature (K)	Pressure (Pa)	Method
Brennen ¹⁶	Pyrex	5×10^{-8}	294	66.5–1330 Pa	afterglow intensity decay in a static system
Wentink ¹⁸	Pyrex	3×10^{-5}	300	> 40 Pa	Pt heat resistance thermometer
Ricard ¹⁹	Pyrex	10^{-5}	300	399 Pa	afterglow intensity measurements
Sancier ²⁰	Pyrex	5×10^{-5}	300	2.4 Pa	diffusion method + measurements of the luminescence and the heat of lumophors excited by N atoms
Marshall ²¹	Pyrex	3×10^{-4}	300	66.5–266 Pa	electron spin resonance measurements
Yamashita ²²	Pyrex	3.2×10^{-6}	300	80–560 Pa	static system + mass spectrometer
Mavroyannis ²³	Pyrex	7.5×10^{-5}	/	333 Pa	flow system + NO titration
Young ²⁴	Pyrex	1.7×10^{-5}	/	133–1596 Pa	flow system+ afterglow intensity measurements
Gordiets ²⁵	Pyrex	2×10^{-4}	<400	266 Pa	kinetic model + actinometry + LIF ¹
Lefevre ²⁶	Pyrex	2×10^{-4}		1500 Pa	numerical procedure of hydrodynamic model and kinetic model + OES ² and NO titration
Oinuma ²⁷	Pyrex	6.8×10^{-5}	323	atmospheric pressure	two-dimensional numerical model
Marshall ²⁸	Quartz	8.3×10^{-4}	300	399–1729 Pa	flow system + ESR ³ measurements
Marshall ²⁸	Quartz	6.9×10^{-4}	598	399–1729 Pa	flow system + ESR measurements
Marshall ²⁸	Quartz	9.6×10^{-4}	779	399–1729 Pa	flow system + ESR measurements
Marshall ²⁸	Quartz	1.51×10^{-3}	995	399–1729 Pa	flow system + ESR measurements
Marshall ²⁸	Quartz	2.04×10^{-3}	1224	399–1729 Pa	flow system + ESR measurements
Evenson ²⁹	Quartz	0.7×10^{-5}	/	400 Pa	flow system + ESR measurements
Evenson ²⁹	Quartz	5.5×10^{-4}	/	400 Pa	flow system + ESR measurements
Belmonte ³⁰	Quartz	9.3×10^{-5} Exp(-3700/RT)	300–823	1500 Pa Ar/N ₂ =1000/50 sccm	numerical procedure of hydrodynamic model + OES and NO titration
Kim ³²	silica	$\sim 10^{-4}$		27 Pa	smith diffusion method + thermocouple probe
Adams ³¹	Si	2.6×10^{-3}	~ 300	133 Pa	two-dimensional model (Chantry equation) + TALIF ¹ calibrated by NO titration
Adams ³¹	Si	1.6×10^{-3}	~ 300	399 Pa	
Adams ³¹	Si	5×10^{-5}	~ 300	665 Pa	
Herron ³³	Pyrex contaminated with water	1.6×10^{-5}	195–450	400 Pa	flow system + NO titration

Table 2: Recombination coefficients for polymer PTFE, plastic foil (the authors give no information on the type of the foil) and ceramics BN

Tabela 2: Rekombinacijska koeficienta za polimer PTFE, plastično folijo (avtorji niso podali informacije o vrsti folije) in keramiko BN

Reference	Material	Recombination coefficient	Temperature (K)	Pressure (Pa)	Method
Ricard ¹⁹	Plastic foil	3×10^{-4}	300	399 Pa	afterglow intensity measurements
Ricard ¹⁹	Teflon	10^{-5}	300	399 Pa	afterglow intensity measurements
Young ²⁴	Teflon	2.9×10^{-5}	/	133–1596 Pa	flow system+ afterglow intensity measurements
Evenson ²⁹	Teflon	0.2×10^{-6}	/	40 Pa	resonant cavity, pure nitrogen plasma
Evenson ²⁹	Teflon	2.5×10^{-5}	/	40 Pa	resonant cavity, nitrogen plasma with oxygen impurities
Oinuma ²⁷	BN	4.8×10^{-5}	323	atmospheric pressure	two-dimensional numerical model
Adams ³¹	BN	2×10^{-4}	300	665 Pa	two-dimensional model (Chantry equation) + TALIF calibrated by NO titration

A similar behaviour as for glasses is found for some polymers. PTFE (teflon) has been known for decades as a very inert material. Not surprisingly, the recombination coefficient for nitrogen atoms has been found as low as for glasses. **Table 2** summarizes the recombination coefficients for two types of polymers. Again, a rather low recombination coefficient of 10^{-4} is due to a lack of adsorption sites for neutral nitrogen atoms on such materials. Similarly low coefficients were also found for

some ceramics. The value for boron nitride is added to **Table 2**. The coefficient is somehow higher than for glasses or Teflon and this fact can be explained by existence of irregularities on the surface of otherwise well bounded material.

Moderately large recombination coefficients are found for many metals including silver (Ag), aluminium (Al), iron (Fe), and molybdenum (Mo). The recombination coefficients for these materials are presented in

¹(TA)LIF – (Two Atom) Laser Induced Fluorescence

²OES – Optical Emission Spectroscopy

³ESR – Electron Spin Resonance

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Table 3: The recombination coefficients for metals such as Ag, Al, Cu, Fe, Mo and for stainless steel. Data for Mo were estimated from the graph $\gamma(T)$ which was published in a relevant reference.

Tabela 3: Rekombinacijski koeficienti za kovine Ag, Al, Cu, Fe, Mo ter za nerjavno jeklo. Podatki za Mo so bili odčitani iz grafa $\gamma(T)$, ki je bil objavljen v ustrezni literaturi označeni v tabeli.

Reference	Material	Recombination coefficient	Temperature (K)	Pressure (Pa)	Method
Hartunian ³⁴	Ag	$<10^{-2}$	300	13–133 Pa	catalytic probe + NO titration
Ricard ¹⁹	Al	6×10^{-4}	300	399 Pa	afterglow intensity measurements
Hartunian ³⁴	Al	$<10^{-2}$	300	13–133 Pa	catalytic probe + NO titration
Adams ³¹	Al	2.8×10^{-3}	300	133 Pa	two-dimensional model (Chantry equation) + TALIF calibrated by NO titration
Adams ³¹	Al	1.8×10^{-3}	300	399 Pa	
Adams ³¹	Al	1.0×10^{-3}	300	665 Pa	
Oinuma ²⁷	Al	1.8×10^{-4}	323	atmospheric pressure	two-dimensional numerical model
Ricard ¹⁹	Cu	2×10^{-3}	300	399 Pa	afterglow intensity measurements
Hartunian ³⁴	Cu	7×10^{-2}	300	13–133 Pa	catalytic probe + NO titration
Lefevre ³⁵	Fe foil with Fe ₂ O ₃ layer	8.2×10^{-2} Exp (-11400/RT)	300–473	1500 Pa Ar/N ₂ =1000/50 sccm	numerical procedure of hydrodynamic model + OES + NO titration
Belmonte ³⁶	Fe ₂ N _{1-x}	1×10^{-2}	823	900 Pa Ar/N ₂ =60%/40%	numerical procedure of hydrodynamic model + OES + NO titration
Belmonte ³⁰	nitrided Fe foil	6.7×10^{-4}	300	1500 Pa Ar/N ₂ =1000/50 sccm	numerical procedure of hydrodynamic model + OES + NO titration
Mozetic ¹³	nitrided Fe foil	0.21	400	100 Pa N ₂ =600 sccm Ar=200–3000 sccm	catalytic probe
Lefevre ³⁷	Fe ₂ O ₃	$58.1 \times$ Exp (-26940/RT)	300–330	1500 Pa Ar with 4.7% N ₂	numerical procedure of hydrodynamic model + OES + NO titration
Hays ³⁸	Mo sputtered on Pyrex	4.4×10^{-3}	283	665 Pa	intensity measurements during plasma decay (continuity equation)
Hays ³⁸	Mo sputtered on Pyrex	4.8×10^{-3}	307	665 Pa	
Hays ³⁸	Mo sputtered on Pyrex	4.9×10^{-3}	317	665 Pa	
Hays ³⁸	Mo sputtered on Pyrex	5.7×10^{-3}	407	665 Pa	
Hays ³⁸	Mo sputtered on Pyrex	7.4×10^{-3}	482	665 Pa	
Hays ³⁸	Mo sputtered on Pyrex	8.4×10^{-3}	557	665 Pa	
Hays ³⁸	Mo sputtered on quartz	6.11×10^{-3}	300	13.3 Pa	intensity measurements during plasma decay (continuity equation)
Hays ³⁸	Mo sputtered on quartz	5.58×10^{-3}	300	27.9 Pa	
Hays ³⁸	Mo sputtered on quartz	2.73×10^{-3}	300	105 Pa	
Hays ³⁸	Mo sputtered on quartz	2.19×10^{-3}	300	154.3 Pa	
Hays ³⁸	Mo sputtered on quartz	2.11×10^{-3}	300	240 Pa	
Hays ³⁸	Mo sputtered on quartz	4.52×10^{-3}	300	45.2 Pa	
Hays ³⁸	Mo sputtered on quartz	3.68×10^{-3}	300	67.8 Pa	
Adams ³¹	Stainless steel	7.5×10^{-3}	~ 300	133 Pa	two-dimensional model (Chantry equation) + TALIF calibrated by NO titration
Adams ³¹	Stainless steel	6.3×10^{-3}	~ 300	399 Pa	
Adams ³¹	Stainless steel	4.8×10^{-3}	~ 300	665 Pa	
Singh ³⁹	Stainless steel	7×10^{-2}	330	173–532 Pa	steady state plasma model + NMS ⁴ and EEDF ⁵ measurements
Oinuma ²⁷	Stainless steel	1.8×10^{-3}	323	atmospheric pressure	Two-dimensional numerical model

⁴NMS – Neutral Mass Spectrometry

⁵EEDF – Electron Energy Distribution Function

Table 4: The recombination coefficients for catalytic materials such as Co, Ir, Pd, Pt and W. The recombination coefficient is temperature independent for Pd and Pt. For other materials the recombination coefficient is temperature dependent and it was estimated from the graph $\gamma(T)$ which was published in a relevant reference.

Tabela 4: Rekombinacijski koeficienti za katalitične materiale kot so Co, Ir, Pd, Pt in W. Rekombinacijski koeficient ni odvisen od temperature za materiala Pd in Pt. Za ostale materiale je temperaturno odvisen in je bil odčitan iz grafa $\gamma(T)$, ki je bil objavljen v ustrezni literaturi označeni v tabeli.

Reference	Material	Recombination coefficient	Temperature (K)	Pressure (Pa)	Method
Halpern ⁴⁰	Co	0.43	418	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.51	446	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.55	556	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.54	605	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.54	656	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.55	676	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.54	791	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.49	882	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.43	938	133 Pa	flow system + NO titration
Halpern ⁴⁰	Co	0.41	987	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.32	1115	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.26	1146	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.34	1202	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.27	1246	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.27	1302	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.37	1400	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.38	1490	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.37	1517	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.38	1591	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.40	1678	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.46	1729	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.45	1779	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.47	1828	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.41	1872	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.45	1921	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.44	1946	133 Pa	flow system + NO titration
Halpern ⁴⁰	Ir	0.48	2020	133 Pa	flow system + NO titration
Halpern ⁴⁰	Pd	0.3	500–1100	133 Pa	flow system + NO titration
Halpern ⁴⁰	Pt	0.31	500–1600	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.21	1614	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.24	1684	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.29	1759	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.32	1821	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.36	1896	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.40	1960	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.43	2023	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.48	2091	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.53	2161	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.57	2235	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.58	2315	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.68	2402	133 Pa	flow system + NO titration
Halpern ⁴⁰	W	0.74	2500	133 Pa	flow system + NO titration

Table 3. One should read the results for these particular materials with some precaution. These materials are known to form native oxide films. The oxide films can be removed prior to experiments with neutral nitrogen atoms but it is rather difficult to keep oxygen free surface in plasma reactors due to the existence of residual atmosphere, especially water vapour. The dissociation energy of water vapour is much lower than for nitrogen molecule so any water that appears in a nitrogen plasma reactor is likely to be dissociated to highly oxidative radicals such as O and OH. These radicals may stick on surfaces even though a lot of precautions were taken in

order to assure appropriate cleanliness of the material surfaces.

The highest recombination coefficients are found for catalytic materials. The results for these particular materials are summarized in **Table 4**. These materials are known for their good chemisorption abilities and transformation of a variety of radicals to stable molecules even at low temperatures. Not surprisingly they are also good catalysts for neutral nitrogen atoms. The recombination coefficient can be as high as 0.4 at room temperature.

4 CONCLUSIONS

An overview of recombination coefficients was presented. The data summarized in this paper are useful for understanding the interaction between nitrogen plasma and solid materials. The first consideration goes for the right choice of the materials used for plasma facing components. More than obvious, catalytic materials should be avoided if a high density of nitrogen atoms in plasma is required. The best material for construction of nitrogen plasma reactors is the one with the lowest recombination coefficient, i.e. Pyrex. Just next to Pyrex is quartz glass. Both materials are high vacuum materials and thus very useful for construction of even large reactors where the purity of processing gas is important. From the recombination point of view polymers are often suitable but in practice they are usually avoided because they are not vacuum materials. If, for any reason glass should be avoided and only metals can be used, the recommended material is aluminium covered by a thin film of alumina (oxide). The oxide film should be compact and rather smooth in order to assure for low recombination coefficient and high stability of surface properties even after prolonged application. Other materials except some ceramics are not suitable as plasma facing components in nitrogen reactors due to a rather high recombination coefficient or rather unpredictable behaviour.

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