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Electron beam induced light emission

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Abstract. Electron beams with a particle energy of typically 12 keV are used for collisional excitation of dense gases. The electrons are sent through ceramic membranes of only 300 nm thickness into gas targets. Excimer light emission from the pure rare gases and from gas mixtures are studied for the development of brilliant VUV and UV light sources. The application of the technology for gas kinetic studies is described and its potential for building very small electron beam pumped lasers is discussed.

PACS. 42.55.Lt Gas lasers including excimer and metal-vapor lasers – 34.50.Fa Electronic excitation and ionization of atoms – 33.20.Ni Vacuum ultraviolet spectra

1 Introduction

Collisional excitation of atoms and molecules by electrons is a key process in all low temperature plasmas. Two conditions can be distinguished. In one case the electrons gain their energy from an electrical field in the plasma. In the other case they are injected into the plasma and loose energy continuously until they are thermalized. The two conditions refer to gas discharges and electron beam excitation, respectively. In nature they are found for example in the form of the lightning stroke and the aurora borealis.

In practical applications such as plasma light sources, arc- and fluorescent lamps, the concept of discharge excitation has dominated over the last century whereas gas excitation and plasma formation by electron beams had almost exclusively been used for fundamental research and in some high power laser or plasma devices. About ten years ago the authors have introduced the concept of low energy electron beam excitation of dense gases for both fundamental research and practical applications [1]. It revisits experiments which had been performed in the late 18 hundreds by Lenard [2]. He had sent electrons through thin aluminium foils (sometimes called "Lenard-windows") into dense gases. Our key innovation was to replace the aluminium windows by extremely thin (300 nm) and vacuum tight ceramic membranes, silicon nitride or combinations of silicon nitride and oxide, in particular. Those membranes can be manufactured on silicon wafer frames using solid state technology.

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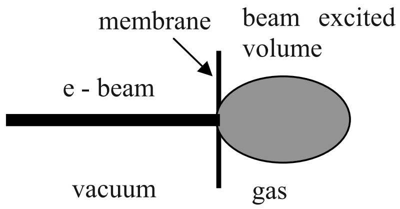
2 General aspects of low energy electron beam induced excitation of dense gases

The basic concept of all experiments described here is shown in the inset of Figure 1. A beam of typically 12 keV electrons is sent from a vacuum part of the system through a 300 nm thick ceramic membrane into a gas target. The electrons are slowed down predominantly by inelastic Coulomb collisions with the electrons in the membrane and the gas, respectively. The energy loss along the trajectory of the individual electrons may be described by the Bethe formula. However, angular scattering is an important process which strongly influences the spatial distribution of the power density deposited in the target as well the overall size of the beam excited volume. Therefore, numerical modelling has to be used to describe the energy deposition precisely. Scaling laws are available from the literature for a limited energy range [3]. They show that the energy deposition depth r_E of an electron beam with particle energy E in the 10 keV range scales like $r_E = \alpha E^n$. The exponent n is on the order of 1.75 and the coefficient α describes the number of target datoms per unit area (in Atoms/cm^2 [3]). Note, that α and thereby the range is inversely proportional to density and therefore also to pressure. Since the scattering leads to an almost spherical beam excited volume with diameter r_E there is a very strong scaling of energy and power deposition P/V in the target with the initial energy E of the electrons and the pressure p which determines the density of the target gas:

$$P/V \propto \frac{E}{(\alpha E^{1.75})^3} \propto p^3\, E^{-4.25}.$$



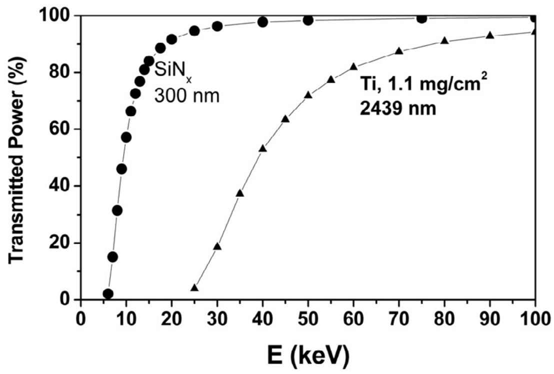


Fig. 1. The drawing on the left side shows the setup schematically. An electron beam enters a gas target from the left through a 300 nm thin silicon nitride (SiN_x) membrane. The figure to the right shows the power which can be transmitted through such an entrance foil versus the energy of the incident electrons in comparison with the power transmitted through a titanium foil with minimum thickness for being vacuum tight. The improved power transmission for SiN_x at reduced electron energies is obvious from this figure. Energies as low as 12 keV are used in practical applications.

This leads to the fact that due to the short range of the electrons, very high power and energy densities can be realized in the target gas with low energy electron beams already for moderate beam currents. Note, that the beams can be applied in both pulsed or continuous mode. Energy deposition is more relevant for the pulsed mode, power deposition for the continuous mode.

The energy and power deposition in the ceramic membrane used as the entrance foil of the gas target is a loss process for the excitation of the gas which is the goal of the experiments described here. A comparison of the loss of kinetic energy of electrons penetrating two different entrance foils is shown in Figure 1. Data were obtained using the model program "CASINO" [4]. The figure clearly demonstrates the advantage of the very thin but vacuum tight and thermally and mechanically stable ceramic membranes in comparison with other entrance foils made from low Z material such as titanium. The thickness of the metal membrane in Figure 1 was chosen as a typical minimum thickness which can be manufactured without pinholes which lead to leakage from the target gas into the vacuum part of the system. Two more detailed studies have been performed to address the issues of the spatial distribution of power deposition in the gas [5] and the energy loss in the entrance foil [6]. The emissivity of light emission from the target gas was used to study the power deposition experimentally and a retardation field method was used to measure the energy loss in the entrance foil without a target gas.

The parameter range for the membranes, gas targets, and electron beams in the practical experiments performed so far can be summarized as follows: membrane size 0.7×0.7 mm^2 and 0.7×40 mm^2 on 5×5 and 10×50 mm^2 wafer pieces, respectively. These membranes withstand pressure differentials of more than 10 and 5 bar, respectively. Continuous electron beams with 12 keV particle energy can be sent through the small membranes with about 10 μA, maximum. The same electron sources as for monochrome cathode ray tubes can be used. In pulsed mode the energy deposition in the membrane has to be kept below a limit which would melt or at least destabilize the material (temperature rise by about 800 K). This limit corresponds for example to 12 keV, 2 A, 100 ns beam pulses which have already been tested using special high power electron guns. The volume which is excited by the beam is for example in the case of 1 bar argon about 1 mm^3. This corresponds to power and energy densities of 120 W/cm^3 and 2.4 J/cm^3 (24 MW during the pulse), respectively for the two examples with dc low-current and pulsed high-current electron guns given above.

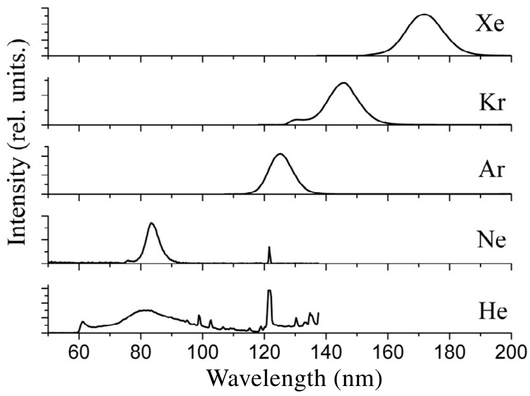


Fig. 2. Emission spectra from the pure rare gases for a target gas pressure of 1 bar.

3 Rare gas excimer emission

The formation of excimer (excited dimer) molecules is the most important process in dense, clean particle beam excited rare gases. This is also the case here and the technology described above can be used to realize compact and brilliant rare gas excimer light sources. The reason is that the rare gas excimer molecules decay radiatively to the repulsive ground state of two rare gas atoms. This aspect has already been discussed in the pioneering publication [1] for this technology. The emission spectra from electron beam excited rare gases of 1 bar are shown in Figure 2. Recently the efficiencies for these light sources have been carefully measured resulting in values of 0.31%, 0.33%, 0.42%, and 0.42% for Ne, Ar, Kr, and Xe, respectively. These efficiency values describe the light output power normalized to the electron beam power deposited in the gas. Details of the measurements are discussed in reference [7]. For obtaining efficient rare gas excimer light sources the cleanliness of the gas is very important. This can be achieved here in a perfect way since the system is free of gas contaminating mechanisms such as erosion of electrodes of a discharge. Hot-metal rare gas purifiers are used for cleaning the target gas.

4 Energy transfer and gas kinetic studies

An aspect which makes electron beam excited dense gas targets very interesting and useful as light sources beyond the rare gas excimer light sources described above, is the fact that energy transfer processes can lead to emission in various wavelengths regions. Also different emission characteristics such as narrow atomic line radiation or specific molecular bands can be observed. A process which has been studied in detail is energy transfer from Ne to H_2 leading to selective and narrow-band emission of the Lyman-α line at 121.6 nm in atomic hydrogen [8,9]. Another light source uses a mixture of argon and water vapour radiating on a molecular band of OH^* around 310 nm [10]. A mixture of argon and nitrogen shows an enhanced emission on the C-B band of nitrogen between 300 and 400 nm. Mixtures of rare gases show energy transfer from the light to the heavier rare gas with emission due to the formation of mixed molecules [11] and for higher concentrations of the heavier species on the rare gas excimer band of these heavier species (first and second continuum) [12].

Gas kinetic process such as energy transfer, collisional quenching, etc. can be studied with the technology described above in a very convenient way. Electron beams can be provided in very short pulses and time resolved optical spectroscopy can be used as the diagnostic tool. Quantitative results of rate constants are obtained by varying pressure and/or gas concentrations and measuring decay times. So called Stern Volmer plots (decay rate versus densities) then provide the rate constants and lifetimes. The great advantage of particle beam excitation for example over pulsed discharges is the fact that the excitation is totally decoupled from the target gas conditions. In particular there are no problems with ignition, arc formation, and ringing of the discharge circuit.

An example for gas kinetic studies using electron beam excitation is related to particle astro physics. Extensive air showers which are formed in the earth's atmosphere by very high energy cosmic ray particles (order of 10^{20} eV) emit predominantly the molecular nitrogen C-B band emission. Observing this fluorescence radiation from air is one of the ways to detect and study high energy cosmic rays in detector arrays like the Pierre Auger detector in Argentina [13]. An accompanying calibration project (AIRFLY) aims at the precise calibration of the fluorescent light produced in air [14]. Since the energy of the cosmic rays is deposited in a long chain of collisional processes, the air shower, all electron beams down to the energy range described here can be useful for these studies. The technique of gas kinetic studies in this context is described in reference [15] and more recent results on the population mechanisms in nitrogen in reference [16].

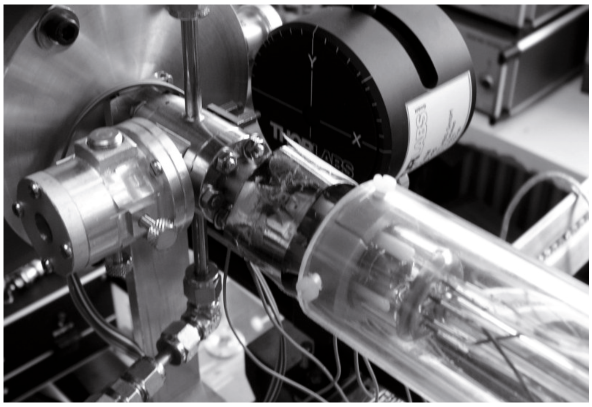


Fig. 3. Photograph of a miniature electron beam pumped laser. The electron gun is inside the 4 cm diameter plastic tube. The laser cell is the steel cylinder with the vertical gas in- and outlet.

5 Miniature electron beam pumped lasers

Low energy electron beam excitation can also be used to realize coherent light sources. Electron beam pumped lasers are the few plasma devices which used electron beams injected into dense gas targets already in the last century. They are normally powerful machines with hundreds of kilovolts acceleration voltage and kiloamperes beam currents sent e.g. through large area titanium foils [17,18]. Some smaller, table top devices with metal entrance foils do exist and are also used for laser experiments [19]. However, due to the material of the entrance foil the acceleration voltage still had to be in the 100 kV range leading to the practical problem of hard X-ray production which requires careful shielding.

The thin ceramic membranes could now be used to scale down the parameters of electron beam pumped lasers dramatically due to the low energy loss in the entrance foil and the high specific energy deposition in the gas discussed above. Therefore, the pumping power density can be kept as high as in the experiments at the powerful machines but with moderate beam parameters (particle energy and beam current). Note, that small beam pumped volumes can also be more easily combined with stable optical laser resonators. Demonstration of laser effect has already been achieved for an infrared Ar–Xe laser operating at a wavelength of 1.73 μm [20]. This laser system is now being studied in more detail in preparation of experiments at shorter wavelengths. A photograph of the present setup is shown in Figure 3. Laser threshold is reached with a 12 keV, 3 μA (36 mW) dc electron beam. The beam pumped volume is on the order of 1 mm^3 and almost spherical. The beam profile is mainly determined by the optical cavity. A 12 kV, 2 A electron gun will be used for shorter wavelength experiments and a 585 nm He–Ne laser (laser system as in Ref. [21]) has already been successfully operated with this device. With on the order of 20 MW/cm^3 which is thereby produced in the heavier rare gases, potential laser operation of the UV and VUV excimer lasers will be studied.

6 Summary and outlook

Introducing extremely thin but vacuum tight and temperature resistant ceramic membranes as a novel type of entrance foil for electron beam pumped plasma devices has lead to a new type of laboratory setup which is ideally suited for studying light emitting processes in dense gases and for performing gas kinetic studies. Brilliant VUV excimer light sources have been developed. They are for example very successfully used in the ion sources of mass spectrometers for so called single photon ionization (SPI) which leads to mass spectra which are essentially free of fragmentation of the analyte molecules [22–24]. In test experiments the electron beam has also been used to induce chemical reactions (so called gas reformation), for example for hydrogen enrichment of fuel gases [25]. Finally, there is a promising perspective for very compact electron beam pumped short wavelength lasers if the technology of combining a pulsed high power electron gun with a gas laser cell can be developed successfully.

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References

1. J. Wieser, D.E. Murnick, A. Ulrich, H.A. Huggins, A. Liddle, W.L. Brown, Rev. Sci. Instrum. **68**, 1360 (1997)
2. P. Lenard, Ann. d. Phys. u. Chem. **51**, 225 (1894)
3. S. Valkealathi, J. Schou, R.M. Nieminen, J. Appl. Phys. **65**, 2258 (1989)
4. P. Hovington, D. Drouin, R. Gauvin, Scanning **19**, 1 (1997)
5. A. Morozov, R. Krücken, A. Ulrich, J. Wieser, J. Appl. Phys. **100**, 093305 (2006)
6. A. Morozov, T. Heindl, C. Skrobol, J. Wieser, R. Krücken, A. Ulrich, Eur. Phys. J. D **48**, 383 (2008)
7. A. Morozov, T. Heindl, R. Krücken, A. Ulrich, J. Wieser, J. Appl. Phys. **103**, 103301 (2008)
8. A. Morozov, R. Krücken, A. Ulrich, T. McCarthy, J. Chem. Phys. **123**, 234311 (2005)
9. T.J. McCarthy, D.E. Murnick, M. Salvermoser, A. Ulrich, J. Phys. B **38**, 3043 (2005)
10. A. Morozov, R. Krücken, T. Ottenthal, A. Ulrich, J. Wieser, Appl. Phys. Lett. **86**, 011502 (2005)
11. A. Morozov, B. Krylov, G. Gerasimov, A. Arnesen, R. Hallin, J. Phys. D **36**, 1126 (2003)
12. T. Efthimiopoulos, D. Zouridis, A. Ulrich, J. Phys. D **30**, 1746 (1997)
13. The Pierre Auger Collaboration, Science **318**, 938 (2007)
14. M. Ave et al., Astropart. Phys. **28**, 41 (2007)
15. A. Morozov, R. Krücken, J. Wieser, A. Ulrich, Eur. Phys. J. D **33**, 207 (2005)
16. A. Morozov, T. Heindl, J. Wieser, R. Krücken, A. Ulrich, Eur. Phys. J. D **46**, 51 (2008)
17. V.M. Orlovsky, V.S. Skakun, V.F. Tarasenko, A.V. Fedenev, Russ. Phys. J. **43**, 372 (2000)
18. J.D. Sethian et al., IEEE Trans. Plasma Sci. **28**, 1333 (2000)
19. O.V. Sereda, V.F. Tarasenko, A.V. Fedenev, Sov. J. Quant. Electron. **21**, 172 (1991)
20. A. Ulrich, C. Nießl, J. Wieser, H. Tomizawa, D.E. Murnick, M. Salvermoser, J. Appl. Phys. **86**, 3525 (1999)
21. A. Ulrich, J. Wieser, A. Brunnhuber, W. Krötz, Appl. Phys. Lett. **64**, 1902 (1994)
22. F. Mühlberger, T. Streibel, J. Wieser, A. Ulrich, R. Zimmermann, Anal. Chem. **77**, 7408 (2005)
23. F. Mühlberger, J. Wieser, A. Morozov, A. Ulrich, R. Zimmermann, Anal. Chem. **77**, 2218 (2005)
24. F. Mühlberger, J. Wieser, A. Ulrich, R. Zimmermann, Anal. Chem. **74**, 3790 (2002)
25. T. Kappes, T. Hammer, A. Ulrich, International Application No.: PCT/DE2002/004641