New, large area, high power and efficient 172nm lamp

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1.) Abstract

A highly efficient, continuous wave 172nm Xenon excimer lamp scalable in power, size and geometry is reported. Data from a prototype device based on multiple corona discharges, operating in dense Xenon gas, confirmed the concept. Results imply that large lamps with uniform VUV-light output exceeding 100mW/cm^2 and wall plug electrical power to VUV light conversion efficiencies approaching 50% can be built.

2.) Introduction

2.1.) Xenon-Excimer 172nm Ultra Violet Light Generation

In order to generate 172nm Xenon excimer, Xe_2^*, radiation, three basic reactions must occur:

(1) $e^- + Xe \rightarrow e^- + Xe^*$

In a first step, a Xenon ground state atom Xe($^1S_0$) must be excited. This usually results from an inelastic collision with a fast electron. The fast electron requires an electron kinetic energy E_e of at least 8.32eV. During the inelastic collision, the electron loses a kinetic energy equal to the excitation energy of Xenon (E(Xe*)=8.32eV), resulting in an excited Xenon atom (Xe*) and a slower electron. Note that if the electrons kinetic energy is **BELOW** E(Xe*), no excitation is possible and the electron does NOT lose its kinetic energy (elastic collision).

(2) $Xe^* + \mathbf{2}\,Xe \rightarrow Xe_2^* + Xe$

An excited Xe* atom and a ground state Xe Atom mutually attract each other, thus making it possible to form an **exci**ted di**mer** molecule, the Xe_2^* **excimer**. The binding energy of Xe_2^* is about 1eV. Note that in order to form the Xe_2^* ecimer molecule, the Xe* must collide with 2 Xe atoms. Xe-atom #1 gets bound to Xe* in the Xe_2^* excimer molecule, while the other Xe-atoms carries away the excess binding energy, thus conserving energy and impulse of the overall system. Without such a 3-body collision, the formation of a Xe_2^* excimer molecule is **not possible**.

(3) $Xe_2^* \rightarrow h\nu$ (172nm) + 2Xe

The energy stored in the Xe_2^* excimer molecule can be released by emitting a **V**acuum **U**ltra **V**iolet (VUV) photon with a wavelength of about 172nm. This wavelength is longer and (thus less energetic) than the light emitted by an excited Xe* atom (147nm) due to the binding energy of the Xe_2^* excimer molecule and the fact that the 2 resulting ground state Xe atoms strongly repel each other (see figure 1). As a result, even very dense Xe gas media (up to more than 10bars) are perfectly transparent (opaque) for 172nm Xe_2^* excimer radiation. The potential energy diagram shown in Figure 1 illustrates reactions (1), (2) and (3).

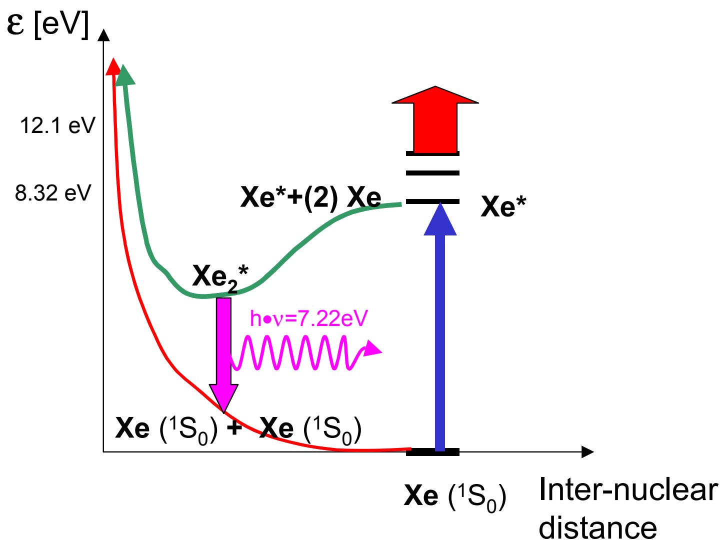


Figure 1: Potential energy of a Xenon dimer, consisting of a ground-state Xe-atom and an excited Xe-atom (Xe*) as a function of inter-nuclear separation (green curve). The repulsive potential energy curve of 2 Xenon ground state atoms is also shown (red curve).

2.2.) Summary

In order to produce Xe_2^* excimer molecules one requires energetic electrons (E_e>8.32eV) to generate Xe* atoms. The Xe* atoms must collide with 2 Xe-atoms to form the Xe_2^* excimer molecule. Since the probability to collide with 2 Xe atoms is proportional to the Xe-pressure squared (p_{Xe}^2) a gas pressure exceeding 300mbars is necessary. Moreover the Xe-gas must stay cold (below about 800 ^{0}C) in order to avoid thermal dissociation of the Xe_2^* excimer molecules prior to emission of the VUV light. Since the energy of the Xe_2^* 172nm light (hν=7.22eV) is smaller than the Xe* excitation energy (E(Xe*)=8.32eV), the Xe_2^* ecimer light will not be trapped by the Xe gas medium and can escape freely (no radiation trapping).

3.) UV-Solutions Inc. 172nm Xe_2^* excimer lamp

3.1) Concept

In order to build a very efficient 172nm Xe_2^* excimer lamp, free electrons are first generated in dense (p_{Xe} 1bar) Xenon gas. Then these electrons drift towards an anode electrode in a sufficiently strong, **C**ontinuous **W**ave (CW), **D**irect **C**urrent (DC) electric field, where they gain kinetic energy until E_e exceeds the the Xe* excitation energy: E_e>E(Xe*)=8.32eV.
An inelastic collision (1) rapidly occurs, generating an excited Xenon atom (Xe*). As long as the electron kinetic energy is below the Xe* excitation energy, E_e< E*(Xe), only elastic collisions can occur, where the electron only loses a negligible amount of energy due to a minute kinetic impulse transfer to the heavy Xe atom.

In such a scenario, it is possible to achieve an electric energy to VUV light emission conversion efficiency in the light-emitting region of:

$\eta_{VUV} \leq (8.32eV/7.22eV) =$ **87%**

Similar to a low pressure Mercury 254nm light source, this **Mercury free R**are **G**as (RG) system channels a large fraction of electrical input power directly into a narrow molecular transition.

The use of inexpensive yet very efficient (90% wall-plug efficiency) DC-current power-supply technology eliminates the need for complex **R**adio **F**requency (RF)-wave-guides, avoiding RF power coupling problems and expensive (RF) power supplies. The inherent impedance generated by electrons colliding with RG atoms in a dense RG-atmosphere allows the use of low ballast impedance and promises theoretical wall-plug conversion efficiencies of electrical energy into VUV-light of more than 50%.

3.2.) Laboratory Prototype

A prototype device with 21 corona needles serving as electron sources has been built. The Xenon pressure could be varied between p_{Xe} = 1 to 4 bars. The diameter of the fused Silica output window was 3.75cm. A voltage of about 10kV was applied to the corona needles resulting in a lamp-current on the order of 1mA. A front view picture of the prototype device can be seen in Photo 1. A schematic drawing of the prototype lamp is shown in figure 2.

Photo 1: Prototype lamp front view

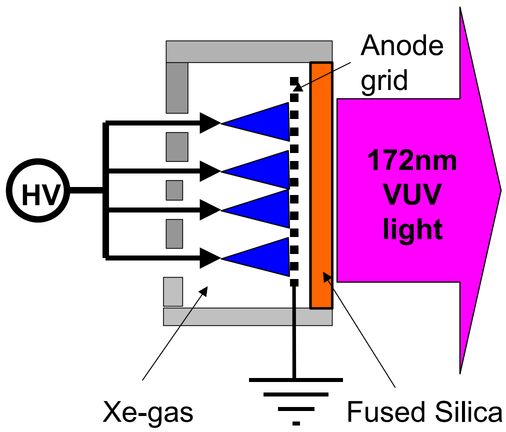


Figure 2: Schematic drawing of the 172nm lamp

3.3.) Experimental Results

A wavelength integrated VUV output (see spectrum in figure 3) at the center of the output window of up to $40mW/cm^2$ was measured using a Hamamatsu model H8025-172nm UV-power meter (absolute-calibrated, traceable to NIST). Lamp output can be varied between

0 and maximal output by simply adjusting the lamp-driver voltage. An electric input energy to VUV-light conversion efficiency of 38% was achieved within the light generating region between needles and anode grid. A view of the active lamp is shown in photo 2.

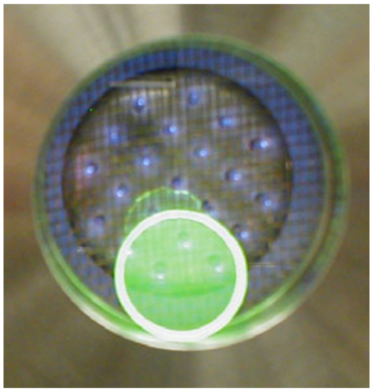


Photo 2: Illuminated prototype 172nm lamp. The green light emitted by a fluorescent glass is due to 172nm VUV light irradiation. Only about 5% of all the light emitted is visible (blue). 95% of the emitted radiation is generated within the 172nm Xe_2^* excimer band.

A spectrum in the spectral rage between 120nm to 300nm of the lamps UV-emission is shown in figure 3:

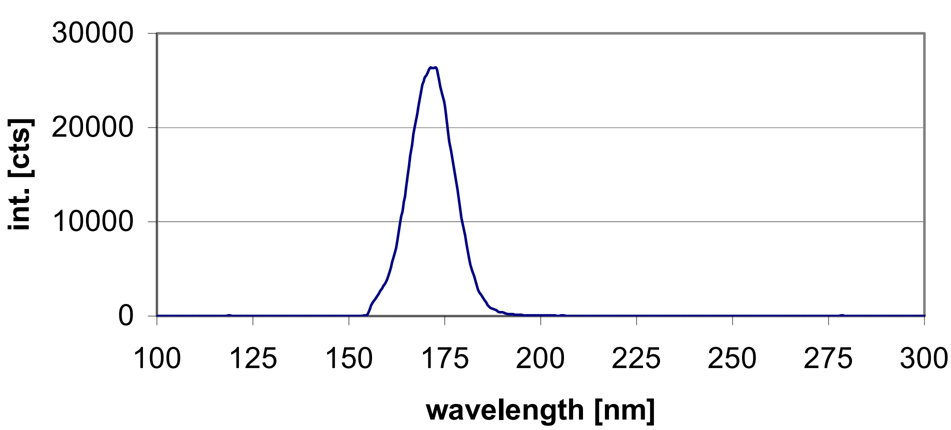
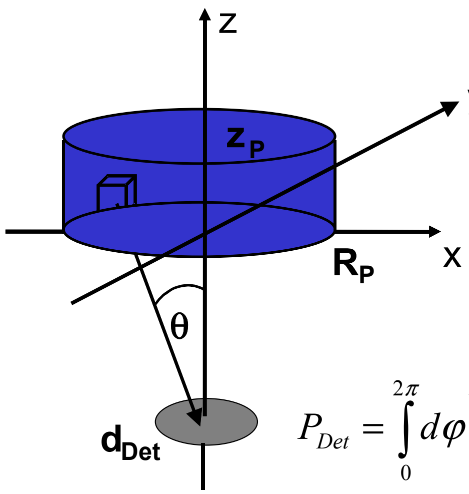


Figure 3: The second continuum Xenon excimer (Xe_2^*) emission at 172nm dominates the emission spectrum.

In order to estimate the VUV output power of a lamp with a larger diameter, the following model was used. It was assumed that the lamps VUV-emitting region has the shape of a homogenous disc with a radius R_P of 2cm and a thickness of z_P of 2.4cm. Moreover, each volume element within the VUV-emitting region radiates the same 172nm VUV radiation power per volume element p_{VUV} (in units of [mW/cm^2]) into the full 4 π solid angle. Then the output power (40mW/cm^2) measured at the center of the output window can be used to estimate p_{VUV}.

The detector used has an active area A_{Det} of 0.27cm^2 and was located at a distance z_D of 1cm from the light emitting disc's surface. Figure 4 illustrates the geometry described above. The power measured by the detector can be derived by simply integrating all the VUV light emitted by each volume element actually hitting the detector surface. The formula resulting form such an integration is shown next to figure 4.



$$P_{Det} = \int_0^{2\pi} d\varphi \int_0^{R_P} r \cdot dr \int_0^{z_P} dz \cdot p_{vuv} \cdot \frac{A_{Det} \cdot \cos\theta}{4 \cdot \pi \cdot (r^2 + (d_{Det} + z)^2)}$$

Figure 4: Schematic drawing showing the VUV-light emitting region (blue) and the surface of the detector's VUV-light sensitive photo cathode. The integral over the complete volume taking into account the solid angle under which the detector appears from each volume element is shown as well.

Once p_{VUV} is known, the formula above can be used again to calculate the output of a lamp with larger lamp radius R_P. Increasing the number of corona points of the prototype lamp (operating under identical conditions) by a factor of 4 and hence increasing the lamp diameter by a factor of **2,** will result in a VUV-output power at the lamp surface of **70mW/cm^2.** The lamp output power will approach 100mW/cm^2 for very large diameters.

4.) Future Developments

4.1) Near Future

Up-scaling and fine tuning of the laboratory prototype to larger areas will result in **extremely efficient** (wall-plug efficiencies exceeding **50%**), **very powerful** (~**100mW/cm**^{2}), flat panel, **large area** (~ **m^2**) **DC-HV** driven (⇒ cost effective), 172nm Xe_2* excimer lamps. Such lamps should have immediate applications in:

Silicon wafer cleaning,
Display cleaning (LCD Production),
Removal of polymers,

UV-Etching,
Photo induced **C**hemical **V**apor **D**eposition,
Ozone (O_3) production,
Cleaning of printed circuit boards,
Photo induced metalization,
Production of ultra-pure water.

If rare-earth atom based **phosphors** are coated on the output window, the 172nm output can be shifted to longer wavelengths, resulting in efficient (⇔cold), powerful (~30mW/cm^2), and mercury free flat panel lamps for:

Germicidal use (250nm) (YPO_4:Pr....225nm to 300nm)),

Curing of coatings and ink
(YBO_3:Pr→250nm to 300nm, $Y_3Al_5O_{12}$:Pr→300nm to 400nm, YF_3:Gd,Pr→311nm)

General lighting purposes
($Ca_5(PO_4)(F,Cl)$:Eu^{3+}→ red, $Ca_5(PO_4)(F,Cl)$: Tb^{3+}→ green,
$Ca_5(PO_4)(F,Cl)$: Eu^{2+}→ blue).

Flat panel large area curing and germicidal lamps also offer the advantage of good **geometric coupling:** Efficient large area flat panel UV light sources should be very well suited for curing and sterilization of flat surfaces. The high efficiency guarantees a relatively cold lamp surface that can be very close to the surface that has to be irradiated. As a result, very little UV light is lost at the edges, while a homogenous power output guarantees a homogenous UV flux on the substrate surface.

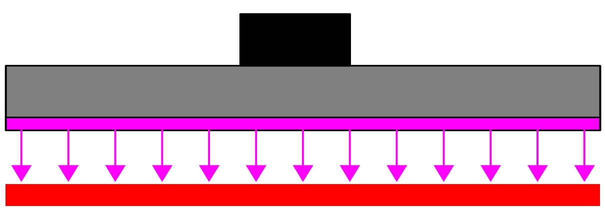


Figure 5: The good geometric coupling between a flat object to be cured (Red) and a cold flat panel lamp is illustrated here.

4.2.) Future Project:

Flat panel**,** low energy **(**10kV, **CW** or pulsed, **DC)** electron beam pumped UV excimer lamps**,** exceeding **1000mW/cm^2** homogenous narrow band UV output at window surface for **curing** and **germicidal** applications**.** Powerful point lamps of many excimer emissions have already been successfully demonstrated. Output wavelength depends on gas-mixture**.** Among others, the following wavelengths are possible:

121nm, 128nm, 145nm, 172nm, 193nm, 206nm, 222nm, 253nm, 290nm, 308nm, 343nm

Efficiencies between **10%** to **40%**, depending on the wavelength chosen, have been achieved. A schematic drawing of such a lamp is shown in figure 4:

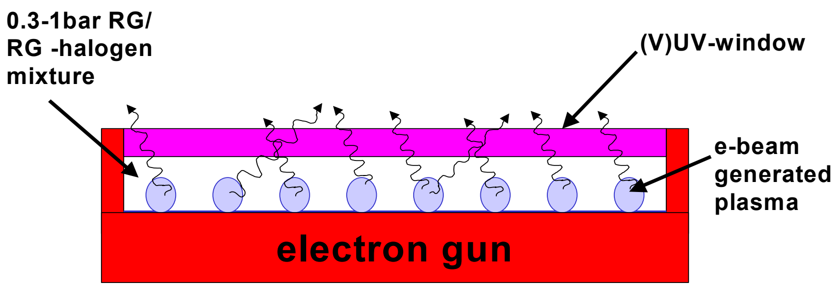


Figure 4: Low energy electron beam pumped flat panel UV-lamp

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