

APPLIED SURFACE SCIENCE



applied surface science

A JOURNAL DEVOTED TO APPLIED PHYSICS
AND CHEMISTRY OF SURFACES AND INTERFACES

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A journal devoted to applied physics and chemistry of surfaces and interfaces

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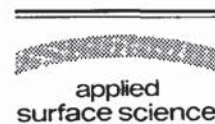
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High-intensity sources of incoherent UV and VUV excimer radiation for low-temperature materials processing

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Abstract

The principles and properties of ultraviolet (UV) and vacuum ultraviolet (VUV) radiation generated by decaying excimer complexes are discussed. Excimer lamps offer high-intensity narrow-band radiation at various UV and VUV wavelengths and reach high efficiencies. They can provide high photon fluxes over extended areas. The use of excimers offers several advantages: excimers can be extremely efficient energy converters transforming electron kinetic energy into UV radiation. No self-absorption is observed in excimer systems. In most cases, excimer forming gas mixtures exhibit one dominant narrow emission band. Excimer systems can be pumped at extremely high power densities before saturation effects start to limit the spontaneous emission. Thus, extremely bright UV and VUV sources can be built. Different types of excimer lamps can be fabricated utilising, repetitively pulsed high power discharges, microwave discharges and dielectric-barrier discharges (silent discharges). For large-scale industrial applications dielectric-barrier discharges using fairly simple discharge configurations currently represent the most mature excimer lamp technology. Recent applications of excimer lamps include photo-deposition of large area or patterned thin metal films, of high- and low-dielectric constant insulating layers, photo-assisted low-temperature oxidation of Si, SiGe and Ge, UV curing, polymer etching and microstructuring of polymer surfaces. Applications investigated so far clearly demonstrate that low cost, high power excimer lamp systems can provide an interesting alternative to excimer lasers for industrial large-scale low-temperature materials processing. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Excimer lamps; Vacuum ultraviolet radiation; Photo-induced materials processing; Patterned metal deposition; Polymer etching; UV curing

1. Introduction

Sources emitting UV/VUV photons in the energy range of 5–15 eV have found a number of interesting applications because such photons are capable of breaking most chemical bonds. They can be used

for a variety of photo-initiated volume and surface processes. Applications include UV curing of photo-reactive polymers, photo-induced thin film deposition of metals, semiconductors and dielectrics, as well as surface cleaning, surface modification and microstructuring of polymeric materials. VUV photons are also utilised on a very large scale in plasma display panels and in mercury-free fluorescent lamps. In these applications phosphors are used to convert VUV excimer radiation to visible light.

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2. Generation of incoherent excimer radiation

2.1. Rare gas excimers, halogen excimers and rare gas halide exciplexes

High density rare gases at around or above atmospheric pressure have the unique ability to efficiently convert electron kinetic energy to electronic excitation energy and rapidly funnel that excitation to a few low lying atom and excimer levels [1]. These systems have been intensively studied with pulsed electron beam pumping for VUV laser applications [2–5]. It has also been demonstrated that simple and efficient excimer lamps can be built using different types of gas discharges to induce excimer formation and subsequently utilising the fluorescence radiation of decaying excimer complexes. Theoretical predictions of the fluorescence efficiency of rare gas excimer radiation lie in the range 45–80% [3,6–9]. At particle densities of about 10^{25} m^{-3} excited species and ions rapidly form excimer complexes. Vibrational relaxation is very fast under such conditions and the spectrum is dominated by the 2nd continuum band originating from the bottom two excimer states. These excimer states do not interact with the ground state and can only decay by radiation. The 2nd excimer continua of the pure rare gases He_2^* , Ne_2^* , Ar_2^* , Kr_2^* , and Xe_2^* peak at 74, 83, 126, 146 and 172 nm, respectively. Typical half widths of the observed fluorescence bands are found to be 10–15 nm. With mixed rare gases the emission can be spread over a wider wavelength region due to the formation of heteronuclear diatomic molecules [10,11].

The energy of excited rare gas atoms and ions can also be efficiently utilised to form halogen excimers X_2^* or rare gas–halide exciplex molecules of the type RgX^* (Rg: Ar, Kr, Xe; X: F, Cl, Br, I) [2–5]. Bound-free transitions are also utilised in these excimers to generate spontaneous VUV/UV emission with high efficiency and even smaller bandwidth, typically in the range 2–4 nm. Table 1 summarises such excimers and their respective peak wavelengths.

2.2. Discharge-driven excimer lamps

High-energy electron beam generators are bulky, expensive and capable of operating at only low repetition rates. For many practical applications excimers generated by an electric discharge inside a closed UV transparent vessel have proved to be much simpler and less expensive. Such excimer lamps, spontaneous emission sources based on excimer formation, can be pumped by pulsed or dc longitudinal discharges, by pre-ionised pulsed transverse discharges, by microwave discharges or by dielectric-barrier discharges (silent discharges). More recently, discharges in supersonic jets, constricted glow discharges and microhollow cathode discharges have also been used to obtain excimer emission. Excimer lamps were initially mainly investigated for spectroscopic purposes [12,13]. During the last decade powerful efficient excimer lamps have been developed that have found several applications in industrial UV induced processes [14–16]. In this presentation, we concentrate on more recent developments concerning high power pulsed excimer sources and on sealed electrodeless lamps with potentially long operating lifetime. Previous literature on laboratory type excimer lamps is reviewed in [6,15,17–20].

2.2.1. High-power excimer flash lamps

Since excimer formation in gas discharges can be achieved at very high power densities in the plasma (10^6 – 10^7 W/cm^3) repetitively pulsed excimer flash lamps with UV peak powers of several megawatts and average UV powers in the kilowatt range have been built [21–26]. For purposes of materials processing, it may be more useful to state the maximum achievable optical power density at the radiating surface which reaches peak values of a few kilowatt per centimetre square and average values up to 1 W/cm^2 . Large area planar excimer UV sources of several 100 cm^2 luminous area can be built. Also in the VUV region high emission powers of 1.5 kW peak value and 140 ns duration have been reported [27].

Table 1
Halogen and rare gas halide excimers with corresponding peak wavelengths in nm

F_2^*	ArCl^*	ArF^*	KrCl^*	KrF^*	XeI^*	Cl_2^*	XeBr^*	Br_2^*	XeCl^*	I_2^*	XeF^*
157	175	193	222	248	253	259	282	289	308	342	354

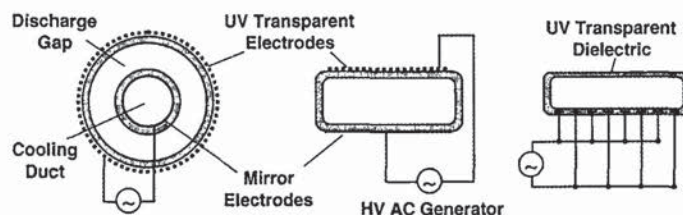


Fig. 1. Sealed cylindrical and planar dielectric-barrier discharge excimer lamp configurations.

The VUV emission of this Kr_2^* lamp peaks at 147 nm with 12 nm spectral width.

2.2.2. Microwave driven excimer lamps

First demonstrations of rare gas excimer fluorescence excited by microwave discharges operating at 2.45 GHz date back to 1954 [28]. Microwave excitation offers the advantage of initiating electrodeless discharges in sealed UV transparent vessels filled with excimer forming gas mixtures. With standard magnetrons also used in microwave ovens extremely cheap and powerful microwave sources are available. For efficient coupling of the microwave energy into the discharge carefully designed waveguides and cavities are required. Based on this principle many excimer lamps with VUV/UV radiation at different wavelengths have been built: Ar_2^* , Kr_2^* , Xe_2^* [28–31], ArF^* [32], KrF^* [33], XeCl^* [34], KrCl^* [35] and F_2^* [36]. With special equipment pulsed microwave power densities of 10^7 W/cm^3 have been reached in high pressure Kr and Xe plasmas [37]. Recent investigations on a microwave driven Xe_2^* excimer lamp claim an intrinsic efficiency of 20–40% [38]. The most powerful commercial excimer lamp is a microwave driven XeCl^* excimer lamp with a UV output of 900 W in a 30 nm wavelength range around 308 nm, corresponding to an overall efficiency of 15% [39]. It uses sealed cylindrical quartz bulbs of 25 cm length mounted in an elliptical microwave cavity which also acts as an optical collection system. This excimer lamp is mainly used for UV curing processes [40,41].

2.2.3. Excimer lamps based on dielectric-barrier discharges

The use of dielectric-barrier discharges to generate excimer radiation has proved to be a very useful concept [6,14–20,42,43]. Their main advantage is simplicity, lack of internal electrodes, high efficiency

and low cost. Sealed lamps of different planar and cylindrical geometries can be designed (Fig. 1). The width of the discharge gap ranges from 0.1 mm to several mm. Filling pressures range from 10^4 to $5 \times 10^5 \text{ Pa}$. In many cases, a third buffer gas (He, Ne) is added to the binary excimer forming mixture. This facilitates ignition and provides additional control over the electron energy distribution. Operating frequencies range from 50 Hz to 1 MHz, applied voltages from a few 100 V to several kilovolt. Commercial excimer lamps now are offered for the wavelengths 126 nm (Ar_2^*); 146 nm (Kr_2^*); 172 nm (Xe_2^*); 222 nm (KrCl^*) and 308 nm (XeCl^*). For UV curing applications cylindrical XeCl^* lamps up to 2 m length are available. Typical efficiencies range from 5–40%. In recent years also powerful and efficient XeI^* and XeBr^* lamps radiating at 253 [44] and 282 nm [45], respectively, have been investigated. Most excimer lamps concentrate their emission in a narrow wavelength region. Even at high electrical input powers cooled versions can operate close to room temperature. Phosphors can be used to transform the UV radiation to visible light. This is the basis of mercury-free fluorescent lamps and of flat plasma display panels with up to 1.5 m picture diagonal.

3. Applications of incoherent excimer radiation

3.1. Material deposition

Using different gas phase precursors a variety of photo-deposition processes was demonstrated using excimer lamps. For the UV induced deposition of amorphous semiconductor layers the 172 nm VUV radiation of the xenon excimer lamp was utilised. Good quality a-Si:H films were obtained by irradiating Si_2H_6 , semiconducting silicon carbide films by adding

C_2H_4 or C_4H_{10} and a-Ge:H films from GeH_4 as a precursor [46–50]. Single- and multilayered films of silicon oxide, silicon nitride, and silicon oxynitride can be deposited by photo-CVD from different mixtures of silane, oxygen, ammonia, and nitrous oxide gases. The highest deposition rates (50 nm/min) have been achieved by irradiating silane and oxygen gas mixtures at a substrate temperature as low as 300°C. Fine tuning of the $Si_xO_yN_z$ composition and the refractive index of the films deposited can also be controlled by varying the composition of the precursor mixtures [51–54].

3.1.1. Excimer UV-lamp induced metal deposition

The first paper using an excimer lamp for the structured deposition of thin metal films by VUV driven CVD was published in 1983 [55]. Radiation from rare gas excimer continua excited in a microwave discharge was used to photo-dissociate trimethylaluminium (TMA) vapour and deposit thin aluminium films. With the availability of more powerful excimer lamps deposition of structured metal films through photo-decomposition of spin-on metallo-organic and organometallic precursors has attracted much attention. Applications are foreseen for high density multichip interconnects, printed circuit boards, high density packaging and multilayers [16]. Much of the work on excimer VUV/UV lamp-induced metal deposition has concentrated on low-temperature decomposition of thin palladium acetate films [14–16,56–60] or other palladium containing

precursors [61,62]. Palladium layers of several nanometre in thickness are deposited which serve as activators for subsequent electroless metal plating processes in which μm -thick copper, nickel or gold layers can be selectively grown on top of the palladium. These metallic overlayers then reach a level of electrical conductivity which is adequate for applications in printed circuit boards and microcircuits.

3.1.2. Photo-deposition of insulating layers of extremely high or low permittivity

For 0.1 μm technology and beyond the SiO_2 gate oxide thickness must be scaled below 2 nm and will present extremely difficult fabrication and reliability problems as well as fundamental quantum mechanical difficulties. Insulating films with a dielectric constant considerably higher than that of SiO_2 can solve this gate dielectric problem, allow the use of a thicker insulating layer with a similar effective capacitance and allow a further decrease in device area. Tantalum pentoxide, Ta_2O_5 , in particular is a promising candidate to replace SiO_2 because of its high dielectric constant k and its compatibility with ultra-large-scale-integrated processing as well as chemical and thermal stability [63–66]. Photo-induced processes using VUV radiation from excimer lamps may help to obtain films with superior properties.

A typical XPS spectrum of a Ta_2O_5 film grown on silicon at a substrate temperature of 350°C by photo-CVD from tantalum ethoxide, $Ta(OC_2H_5)_5$, with a Xe_2^* excimer lamp is shown in Fig. 2. Peaks of Ta 4f,

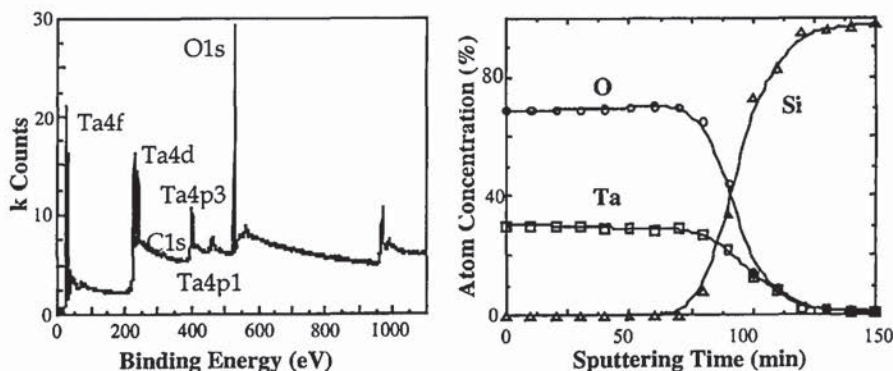


Fig. 2. XPS spectrum of the films deposited at a substrate temperature of 350°C (left) and XPS depth profile of tantalum oxide with a thickness of 95 nm deposited on silicon (right).

Ta 4d and O 1s are easily identified while that for C 1s (around 285 eV) is very small. The XPS depth profile of a 95 nm thick tantalum oxide layer grown at 350°C is also shown where the oxygen and tantalum concentrations can be seen to be quite uniform throughout the Ta₂O₅ film. Their respective concentrations are calculated to be about 70 and 29%, respectively, and the atom ratio of O/Ta of about 2.4, is close to the stoichiometric ratio of 2.5 for Ta₂O₅. The measured average transmittance of about 90% in the visible region of the spectrum for films grown at temperatures between 250–400°C is characteristic of very high quality Ta₂O₅. The values of the optical band-gap energy (4.16 eV) and the dielectric constant (24) are very close to those recorded for Ta₂O₅ grown by other methods [67]. Leakage current densities of 10^{−8} A/cm² for the films grown by this photo-CVD technique are comparable to those obtained for films annealed at high temperatures between 600 and 1000°C [68,69]. Clearly, the photo-assisted processing can produce high quality Ta₂O₅ layers at much lower temperature than the other growth techniques.

When the feature sizes of ultra-large scale integrated (ULSI) devices are reduced to low sub-micron dimensions the performance at the metal interconnect level becomes crucial. Propagation delay, cross talk noise, and power dissipation at the metal interconnects become significant due to resistance–capacitance (RC) coupling. This RC time delay can be reduced either by the incorporation of low permittivity dielectric materials and/or high conductivity metals. Polymeric films are most promising in this respect [70]. Polyimides are particularly attractive not only because of their low dielectric constants, but also because of their ease of application and patterning, and their high thermal stability [71]. Recent work on photo-induced deposition has highlighted a significant role of UV photons in the curing of polyamic acid films [72]. The results demonstrate that a polyamic acid film is completely transformed to polyimide by a UV curing step at 150°C, while a thermally cured sample is only partly transformed. Compared with conventional furnace processing, the photo-induced curing of the polyimide provided both reduced processing time and temperature. In particular, the leakage current density of the irradiated polymer was over an order of magnitude smaller than that of layers obtained by thermal processing. More recent work on low tem-

perature photo-induced formation of low *k* porous silica films from TEOS sol–gel solutions using an excimer lamp show that the dielectric constant of the films strongly depends on the substrate temperature [73]. Tunable dielectric constants between 1.7 and 3.6 can readily be obtained by this technique and have high potential applicability as interlayer dielectric layers for advanced ultra-large-scale-integrated devices.

3.2. UV assisted oxidation of Si and Ge

The continuous reduction of linear dimensions in microelectronic devices has imposed a severe limitation on the thermal budgets associated with the various process steps employed in fabrication. Particular attention has been paid to various low-temperature alternatives to traditional thermal oxidation of Si, typically performed at about 1000°C. The use of excimer lamps can considerably enhance the oxidation rate at low temperatures. Thermal oxidation of Si is negligible at 450°C, while the Xe excimer-lamp induced oxidation rate at 250°C, due to ozone produced by the VUV radiation, is more than three times that of photo-induced oxidation of Si using a low pressure Hg lamp at 350°C [74]. The fixed oxide charge number density of 4.5 × 10¹⁰ cm^{−2} is comparable to some of the best values reported for thermally grown oxide on Si at a high temperature of 1030°C [75]. Very recently, this work has been extended to study the direct photo-oxidation of Ge at temperatures <400°C using a 172 nm excimer lamp. An oxidation rate of 0.1 nm/min was obtained which is significantly faster than conventional thermal oxidation. According to FTIR and XPS analysis, the oxide layers grown have a composition identical to that of thermally grown GeO₂ [76].

3.3. Photo-etching and microstructuring of polymer surfaces

Dry etching of photo-resists and various polymers has become an important process step in the fabrication of microelectronic devices. Photo-etching of various polymers e.g. PMMA (poly-methylmethacrylate), PI (polyimide), PET (poly-ethyleneterephthalate), PTFE (polytetrafluoro-ethylene) has been demonstrated using different wavelength excimer

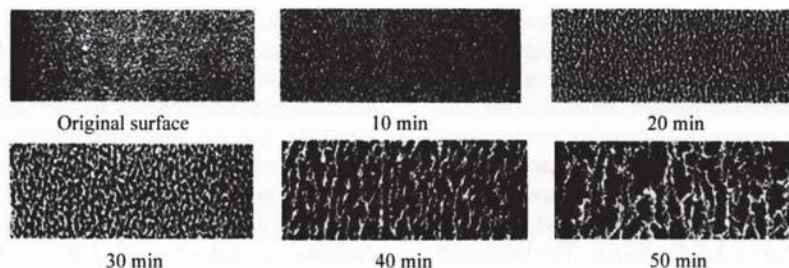


Fig. 3. Surface morphology change of PET irradiated for different times with a KrCl^* excimer lamp (irradiance: 25 mW/cm^2 , $\lambda = 222 \text{ nm}$, exposure times: 0, 10, 20, 30, 40 and 50 min, frame size: 6 by 19 μm).

lamps (172, 222, and 308 nm) [58,77–81]. In the case of PTFE, etch rates as high as $1 \mu\text{m/min}$ have been achieved. These high material removal rates suggest that excimer lamps will also find applications in the microstructuring of large area polymer surfaces.

Polymer surfaces are often smooth and chemically unreactive. Photo-induced etching can lead to physical and chemical alteration of surface properties. This has become a field of considerable technical importance. It can be used to improve the adhesion of coatings as well as wettability, bondability and printability of polymers by changing the morphology and chemical surface properties [82]. The roughness of the UV irradiated area can be controlled by suitable choice of parameters (wavelength, exposure time, gas environment, pressure, etc.) and depends also on the properties of the material to be etched. Recent work on PET using excimer lamps shows a pronounced increase of surface roughness with rising exposure time [79]. SEM pictures taken after different exposure times with a KrCl^* excimer lamp at $\lambda = 222 \text{ nm}$ are presented in Fig. 3.

UV irradiation of PET leads to the formation of ripples at the surface. Ripple dimensions and roughness features increase with exposure time. Compared to pulsed excimer laser irradiation at 248 and 308 nm [82–84], the characteristic scale size of the roughness features is much smaller. For the excimer lamp etching of polymers, no threshold fluence and no significant temperature rise was observed [85]. Consequently no thermal damage such as melting or bubble formation was found in and around the exposed region. The experiments suggest that the etching process with incoherent UV radiation originating from excimer lamps is mainly of photolytical nature.

4. Summary

Efficient generation of powerful narrowband incoherent UV and VUV excimer radiation can be achieved utilising transient excimer complexes formed in special gas discharges. With rare gas dimers and rare gas halide exciplexes peak emissions centred at different wavelengths covering the whole VUV and UV range can be realised. Sealed VUV/UV sources filled with excimer forming gas mixtures and fitted with external electrodes promise long operating lifetimes and allow a variety of geometrical shapes including cylindrical and various flat planar configurations. During the past decade, a number of exciting novel applications have been found for these excimer lamps. With suited gas phase precursor substances or in the form of spin-on films large area or patterned metal, semiconducting and dielectric thin films of high quality can be obtained by UV induced processes. In addition, low temperature oxidation of Si, Ge, and SiGe as well as UV induced dry etching of polymer surfaces was demonstrated. Today it is quite apparent that low temperature materials processing controlled by ultraviolet radiation will find a number of important technical applications.

References

- [1] D.C. Lorents, *Phys. C* 82 (1976) 19.
- [2] S. Watanabe, H. Kashiwagi, *Oyo Buturi (Japan)* 46 (1977) 978 (in Japanese).
- [3] Ch.K. Rhodes (Ed.), *Excimer Lasers*, Springer, New York, 1979 and 1984.
- [4] I.S. Lakoba, S.I. Yakovlenko, *Sov. J. Quantum Electron.* 10 (1980) 389.

- [5] G.N. Gerasimov, B.E. Krylov, A.V. Loginov, S.A. Shchukin, *Sov. Phys. Usp.* 35 (1992) 400.
- [6] B. Eliasson, U. Kogelschatz, *Appl. Phys. B* 46 (1988) 299.
- [7] A.P. Gochelashvili, A.V. Dem'yanov, J.V. Kochetov, L.R. Yangurazova, *Laser Phys.* 3 (1993) 140.
- [8] V.V. Ivanov, K.S. Klopovskii, Yu.A. Mankelevich, A.T. Rakhimov, T.V. Rakhimova, G.B. Rulev, V.B. Saenko, *Laser Phys.* 6 (1996) 654.
- [9] F. Vollkommer, L. Hitzschke, in: G. Babucke (Ed.), in: *Proceedings of the 8th International Symposium on Science Technology Light Sources (LS-8)*, Greifswald, Germany, 1998, pp. 51–60.
- [10] S. Kubodera, M. Honda, M. Kitahara, J. Kawanaka, W. Sasaki, K. Kurosawa, *Jpn. J. Appl. Phys.* 34 (1995) L618.
- [11] G.N. Gerasimov, G.A. Volkova, G.N. Zvereva, in: G. Babucke (Ed.), in: *Proceedings of the 8th International Symposium on Science Technology Light Sources (LS-8)*, Greifswald, Germany, 1998, pp. 248–249.
- [12] Y. Tanaka, *J. Opt. Soc. Am.* 45 (1955) 710.
- [13] E.N. Pavlovskaya, A.V. Yakovleva, *Opt. Spectrosc. (USSR)* 54 (1983) 132.
- [14] U. Kogelschatz, B. Eliasson, H. Esrom, *Mater. Design* 12 (1991) 251.
- [15] U. Kogelschatz, *Appl. Surf. Sci.* 54 (1992) 410.
- [16] I.W. Boyd, J.-Y. Zhang, *Nucl. Inst. Methods Phys. Res. B* 121 (1997) 349.
- [17] B. Eliasson, U. Kogelschatz, *IEEE Trans. Plasma Sci.* 19 (1991) 309.
- [18] U. Kogelschatz, *Pure Appl. Chem.* 62 (1990) 1667.
- [19] B. Gellert, U. Kogelschatz, *Appl. Phys. B* 52 (1991) 14.
- [20] U. Kogelschatz, in: V. Palleschi, D.P. Singh, M. Vasselli (Eds.), in: *Proceedings of the XX International Conference on Phenomena in Ionized Gases (ICPIG-XX)*, Barga, Italy, 1991, pp. 218–227 (invited papers).
- [21] T. Gerber, W. Luethy, P. Burkhardt, *Opt. Commun.* 35 (1980) 242.
- [22] V.M. Borisov, A.M. Davidovskii, O.B. Kristoforov, *Sov. J. Quantum Electron.* 12 (1982) 1403.
- [23] A.M. Boichenko, V.S. Skakun, V.F. Tarasenko, E.A. Fomin, S.I. Yakovlenko, *Laser Phys.* 4 (1994) 635.
- [24] V.F. Tarasenko, M.I. Lomaev, A.N. Pachenko, V.S. Skakun, E.A. Sosnin, in: R. Kossowsky, M. Jelinek, R.F. Walter (Eds.), *High Power Lasers*, Kluwer, Dordrecht, 1996, pp. 331–345.
- [25] M.I. Lomaev, A.N. Pachenko, V.S. Skakun, E.A. Sosnin, V.F. Tarasenko, M.G. Adamson, B.R. Myers, F.T. Wang, *Laser Particle Beams* 15 (1997) 339.
- [26] S. Bollanti, G. Clementi, P. Di Lazzaro, F. Flora, G. Giordano, T. Letardi, F. Muzzi, G. Shina, Z.E. Zheng, *IEEE Trans. Plasma Sci.* 27 (1999) 211.
- [27] J. Kawanaka, T. Shirai, S. Kubodera, W. Sasaki, *Proc. SPIE* 3574 (1998) 466.
- [28] Y. Tanaka, M. Zelikoff, *J. Opt. Soc. Am.* 44 (1954) 254.
- [29] P.G. Wilkinson, Y. Tanaka, *J. Opt. Soc. Am.* 45 (1955) 344.
- [30] R.E. Huffman, J.C. Larrabee, Y. Tanaka, *Appl. Opt.* 4 (1965) 1581.
- [31] P.G. Wilkinson, E.T. Byram, *Appl. Opt.* 4 (1965) 581.
- [32] H. Kumagai, M. Obara, *Appl. Phys. Lett.* 55 (1989) 1583.
- [33] H. Kumagai, M. Obara, *Jpn. J. Appl. Phys. Lett.* 28 (1989) L 2228.
- [34] S.B. Hassal, E.A. Ballik, *J. Appl. Phys.* 70 (1991) 1042.
- [35] S.B. Hassal, E.A. Ballik, *Can. J. Phys.* 69 (1991) 699.
- [36] H. Kumagai, K. Toyoda, *Appl. Phys. Lett.* 59 (1991) 2811.
- [37] O.A. Zakharenko, A.A. Kuznetsov, V.N. Slinko, S.S. Sulakshin, *Sov. J. Quantum Electron.* 20 (1990) 813.
- [38] J.D. Ametep, J. Diggs, D.M. Manos, M.J. Kelley, *J. Appl. Phys.* 85 (1999) 7005.
- [39] J.D. Frank, M. Cekic, C.H. Wood, in: *Proceedings of the 32nd Microwave Power Symposium*, Ottawa, CA, 1997, pp. 60–63.
- [40] R. Mehnert, in: R. Mehnert, A. Pincus, I. Janorski, R. Stowe, A. Berejka (Eds.), *UV & EB Curing Technology & Equipment*, Wiley, New York, 1999, pp. 83–105.
- [41] R. Mehnert, in: *Proceedings of the RadTech Europe 99*, Berlin, 1999, pp. 303–310.
- [42] K. Stockwald, M. Neiger, *Contrib. Plasma Phys.* 35 (1995) 15.
- [43] J.-Y. Zhang, I.W. Boyd, *J. Appl. Phys.* 80 (1996) 633.
- [44] J.-Y. Zhang, I.W. Boyd, *J. Appl. Phys.* 84 (1998) 1174.
- [45] Z. Falkenstein, J.J. Coogan, *J. Phys. D: Appl. Phys.* 30 (1997) 2704.
- [46] F. Kessler, H.-D. Mohring, G.H. Bauer, *Mater. Res. Soc. Symp. Proc.* 192 (1990) 559.
- [47] F. Kessler, G.H. Bauer, *Appl. Surf. Sci.* 54 (1992) 430.
- [48] C. Manfredotti, F. Fizzotti, M. Boero, G. Piatti, *Appl. Surf. Sci.* 69 (1993) 127.
- [49] C. Manfredotti, F. Fizzotti, C. Osenga, G. Amato, L. Boarino, *Phys. Stat. Sol. A* 135 (1993) 191.
- [50] X. Redondas, P. Gonzáles, B. León, M. Pérez-Amor, *Surf. Coat. Technol.* 100/101 (1998) 160.
- [51] P. Bergonzo, U. Kogelschatz, I.W. Boyd, *Appl. Surf. Sci.* 69 (1993) 393.
- [52] P. Gonzáles, E. Garcia, J. Pou, D. Fernández, J. Serra, B. León, M. Pérez-Amor, *Thin Solid Films* 421 (1993) 348.
- [53] P. Bergonzo, I.W. Boyd, *J. Appl. Phys.* 76 (1994) 4372.
- [54] P. Bergonzo, I.W. Boyd, *Microelectron. Eng.* 25 (1994) 345.
- [55] A.R. Calloway, T.A. Galantowicz, W.R. Fenner, *J. Vac. Sci. Technol. A* 1 (1983) 534.
- [56] H. Esrom, J. Demny, U. Kogelschatz, *Chemtronics* 4 (1989) 202.
- [57] H. Esrom, U. Kogelschatz, *Thin Solid Films* 218 (1992) 231.
- [58] J.-Y. Zhang, Ph.D. Thesis, Karlsruhe University, Germany, 1993.
- [59] J.-Y. Zhang, H. Esrom, I.W. Boyd, *Appl. Surf. Sci.* 96–98 (1996) 399.
- [60] J.-Y. Zhang, I.W. Boyd, *Thin Solid Films* 318 (1998) 234.
- [61] E.J. Lafferty, E.D.J. Macauley, K.F. Mongey, P.V. Kelly, G.M. Crean, *Appl. Surf. Sci.* 100/101 (1998) 80.
- [62] J.-Y. Zhang, I.W. Boyd, S. Draper, *Surf. Coat. Technol.* 100/101 (1998) 469.
- [63] S. Tanimoto, M. Matsui, K. Kamisako, K. Kuroiwa, Y. Tarui, *J. Electrochem. Soc.* 139 (1992).
- [64] Y. Nishimura, K. Tokunaga, M. Tsuji, *Thin Solid Films* 226 (1993) 144.
- [65] K.W. Kwon, C.S. Kang, S.O. Park, H.K. Kang, S.T. Ahn, *IEEE Trans. Electron. Dev.* 43 (1996) 919.

- [66] J.-Y. Zhang, B. Lim, V. Dusastre, I.W. Boyd, *Appl. Phys. Lett.* 73 (1998) 2299.
- [67] H. Demiryont, J.R. Sites, K. Geib, *Appl. Opt.* 24 (1985) 490.
- [68] J.L. Autran, P. Paillet, J.L. Leray, R.A.B. Devine, *Sens. and Actuators A* 51 (1995) 5.
- [69] K.A. McKinley, N.P. Sandler, *Thin Solid Films* 290/291 (1996) 440.
- [70] P. Singer, *Semiconductor Int.* Oct. (1994) 34.
- [71] S.P. Murarka, *Solid State Technol.* 39 (1996) 83.
- [72] J.-Y. Zhang, I.W. Boyd, *Opt. Mater.* 9 (1998) 251.
- [73] J.-Y. Zhang, I.W. Boyd, E-MRS Spring Meeting 1999 (to be published: *Appl. Surf. Sci.* 2000).
- [74] I.W. Boyd, V. Craciun, A. Kazor, *Jpn. J. Appl. Phys.* 32 (1993) 6141.
- [75] G. Eftekhari, *J. Electrochem. Soc.* 140 (1993) 787.
- [76] V. Craciun, B. Hutten, D.E. Williams, I.W. Boyd, *Electron. Lett.* 34 (1998) 71.
- [77] H. Esrom, J.-Y. Zhang, U. Kogelschatz, *Mat. Res. Symp. Proc.* 236 (1992) 39.
- [78] J.-Y. Zhang, H. Esrom, U. Kogelschatz, G. Emig, *Appl. Surf. Sci.* 69 (1993) 299.
- [79] J.-Y. Zhang, I.W. Boyd, H. Esrom, *Surf. Interface Anal.* 24 (1996) 718.
- [80] J.-Y. Zhang, H. Esrom, G. Emig, U. Kogelschatz, in: K.L. Mittal (Ed.), *Polymer Surface Modification: Relevance to Adhesion*, VSP, Utrecht, 1996, pp. 153–185.
- [81] H. Esrom, J.-Y. Zhang, U. Kogelschatz, in: K.L. Mittal, K.-W. Lee (Eds.), *Polymer Surfaces and Interfaces: Characterization, Modification and Application*, VSP, Utrecht, 1997, pp. 27–35.
- [82] J.E. Andrew, P.E. Dyer, D. Forster, P.H. Key, *Appl. Phys. Lett.* 43 (1983) 717.
- [83] S. Lazare, P.D. Hoh, J.M. Baker, R. Srinivasan, *J. Am. Chem. Soc.* 106 (1984) 4288.
- [84] T. Nakata, F. Kannari, M. Obara, *Optoelectron. Devices Technol.* 8 (1993) 179.
- [85] J.-Y. Zhang, H. Esrom, U. Kogelschatz, G. Emig, *J. Adhesion Sci. Technol.* 8 (1994) 1179.