A short note on technical analysis of excimer lasers, their optimization for laser corneal refractive surgery, and novel applications[1]

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Abstract

Excimer Lasers are very useful for a variety of applications including semiconductor manufacturing, materials processing, materials marking, micromaching, fiber Bragg gratings, high temperature superconducting films, and most importantly the eye surgery. The purpose of the present paper is to provide the technical analysis of the designing of these lasers, besides giving a brief discussion of the mathematical considerations in the laser corneal refractive surgery, and also a qualitative review of the recent important investigations on their novel applications. It is hoped that this paper should be really useful for the new researchers, and also the technologists in the field.

Keywords: Excimer lasers, excited dimer, ArF lasers, XeCl lasers, laser corneal refractive surgery.

Resumen

Los láseres de excímeros son muy útiles para una variedad de aplicaciones, incluyendo la fabricación de semiconductores, procesamiento de materiales, materiales de marcado, micromaching, rejillas de fibra de Bragg, películas superconductoras de alta temperatura, y lo más importante la cirugía del ojo. El propósito del presente trabajo es proporcionar el análisis técnico del diseño de estos láseres, además de una breve discusión de las consideraciones matemáticas en la cirugía láser refractiva de córnea, y una revisión cualitativa de las recientes investigaciones importantes sobre sus nuevas aplicaciones. Se espera que este documento sea realmente útil para los nuevos investigadores, así como para los tecnólogos en la materia.

Palabras clave: Láser de excímeros, dímero excitado, láser ArF, láser XeCl, cirugía refractiva corneal con láser.

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I. INTRODUCTION

An excimer laser is a form of ultraviolet laser, commonly used in the fabrication of microelectronic devices including semiconductor integrated circuits, besides having applications in eye surgery, and micromachining. In fact, excimer [1] may be used to specify a family of lasers with similar output characteristics like:
(i) all emitting powerful pulses lasting nanoseconds or tens of nanoseconds, with wavelengths in or near the ultraviolet,
(ii) the lasing medium is a diatomic molecule, or dimer, having component atoms bound in the excited state, and not in the ground state.

The term excimer means excited dimer, having molecules in the form of rare gas halides like ArF, KrF, XeF and XeCl, which interestingly, though not existing in nature, can be easily produced by passing an electrical discharge through a suitable gas mixture of rare gas ~1-9%, a halogen donor concentration ~ 0.1 to 0.2%, and He or Ne gas, the last being used for assisting the energy transfer. The importance of these lasers has drawn the attention of the researchers [2, 3].

A. Construction

The fabrication of the excimer lasers and the materials used are quite different from those in the commonly employed gas and solid state lasers. Since the gases employed are corrosive in nature, the excimer lasers are fabricated from stainless steel, and have polyvinyl and teflon components.

A schematic of the excimer laser is shown in Figure 1. It is interesting to note that in general the discharge is transverse, and the electrodes are relatively long, flat and made from nickel or brass. A pre-ionisation pulse has to be used to establish uniform excitation. The laser gas is

[1] Some of the technical analysis presented in this paper is on the basis of the discussions with the researchers of the Photonics Group, Department of Physics, Indian Institute of Technology, Delhi, during the association of the author with the group, as Project Scientist in the Project on “Investigations on Optical correlators with high capacity holographic memory” (From 17-06-2006 to 15-02-2009), sponsored by the DRDO, Ministry of Defence, Government of India, New Delhi, India.

observed to degrade after the usage, and so the laser cavity is sealed and refilled, whenever required.

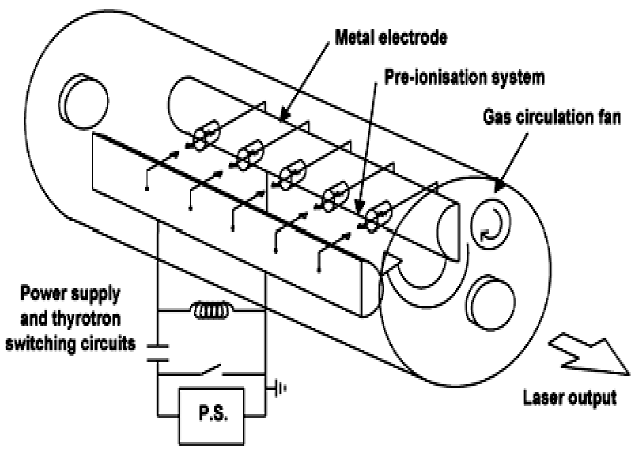

FIGURE 1. Excimer laser schematic Figure courtesy www.twi-global.com.

There is another great difference between excimer laser and the other gas lasers: though the rear cavity mirror is highly reflective, the output mirror does not require a reflective coating, because these lasers have high gain. The window material used is mostly MgF_2, which is more transparent than quartz or fused silicon at short wavelength, though sapphire is also used in the ArF lasers. In case of excimer repetitive pulsed laser, the average output (in watts) is obtained by multiplying the pulse energy (in joules) with the repetition rate (number of pulses per second), and the typical average powers are in the range 1W to 120W.

Interestingly, the average power is not always obtained by taking the product mentioned here, as the energy produced per pulse decreases after the repetition rate exceeds a certain value. Also, the lasers with similar average power may have quite different output characteristics *e.g.* A xW average power laser can be obtained by producing 10x pulses of 10xmJ each, or x pulses of 1J each. Another characteristic of these lasers is that for the standard stable resonator configurations, quite divergent beams ~ 2cm x 1cm can be generated because of the fact that the available gain is relatively high, the efficiency of a discharge driven commercial KrF laser being ~ 2%.

The fabrication of an excimer laser is based typically on using a combination of a noble gas like argon, krypton, or xenon; and a reactive gas like fluorine or chlorine. The operation principle is simple, the creation of a pseudo-molecule called an excimer or exciplex (in the case of noble gas halides), under the suitable conditions of electrical stimulation and high pressure, which interestingly can exist only in an energized state, and also can give rise to laser light in the ultraviolet range. The first excimer laser developed by Basov *et al* in 1970, used $Xe_{(g)}$, and lased at 172 nm. Four years later, first exciplex excimer laser was simutaneously developed by University of Cambridge, Kansas State University, and Avco Everett Research laboratory. Then in 1977, the first commercial excimer/exciplex laser of 10 MW power was made available by M/s Lambda Physik.

B. Operation

The excited dimer is a short lived molecule formed from one or two species, at least one, being in an electronically excited state, and interestingly, may not be stable in ground state.

The excimer laser is an electron pumped laser, having dimer (excimer)/complex (exciplex) formation, in which the laser radiation is due to the relaxation from excited state dimer to ground state, as given below:

$$e^- + A \rightarrow A^*$$

$$A^* + B \rightarrow AB^* \rightarrow AB + h\nu$$

Immediately, afterwards, another action takes place, which can be represented as

$$AB \rightarrow A + B$$

Two main points to be noted in this case are: (i) the lower state does not exist; and (ii) there are no rotational/vibrational bands.

The laser radiation due to the relaxation from excited state dimer to ground state, is as given in the following figure:

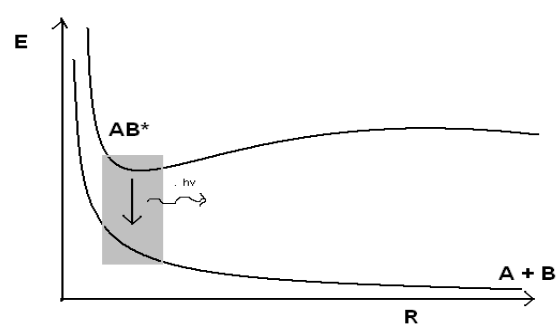

FIGURE 2. Laser radiation due to the relaxation from excited state dimer to ground state.

Thus, we see that the laser action in an excimer molecule takes place because it has a bound (associative) excited state, along with a repulsive (dissociative) ground state, which is due to the fact that the noble gases Xe and Kr are highly inert and therefore, usually are unable to form chemical compounds. However, when in an excited state (induced by an electrical discharge or high-energy electron beams, which produce high energy pulses), they can form temporarily bound molecules with themselves (dimers) or with halogens (complexes) such as fluorine and chlorine.

The excited compound can give up its excess energy by undergoing spontaneous or stimulated emission, resulting in a strongly repulsive ground state molecule, which very quickly (~ a picosecond) dissociates back into two unbound atoms, and thus forms a population inversion.

An excimer laser is a laser which produces energy in the ultraviolet spectrum. This type of laser has a number of applications, with one of the most important being, the use in opthalmologic procedures like LASIK eye surgery. The earliest versions of excimer lasers were developed in the 1970s in Russia, and by the 1980s, the potential applications of this laser in surgery were being recognized.

Regulatory agencies have approved a number of excimer laser designs for use in eye surgery.

The laser contains a mixture of gases which are excited with electricity to produce a dimer, a type of pseudomolecule. The term "excimer laser" is derived from "excited dimer." The excimer laser is a type of cool laser, meaning that it does not generate heat, and it can be highly precise, which is critical for operations in which fine detail is required. When objects are targeted with an excimer laser, they cannot absorb the energy, and as a result, the upper layers of the object start to break down. The energy dissipates quickly, limiting risks of lingering radiation.

In eye surgery, the excimer laser is used to precisely ablate the eye for vision correction. While the actual process sounds rather brutal as described, the excimer laser can be tightly controlled to target the desired area without causing residual damage. Before surgery, the laser is always carefully calibrated and checked to confirm that it is in working order, to reduce the risks for the person undergoing treatment.

There are, of course, risks to surgery with an excimer laser. While the technology is improving all the time, things can still go wrong, or a surgeon may not be fully competent with the laser, which could put the person at risk. For this reason, it is important to thoroughly read and go over the informed consent form signed before surgery, to understand the known risks associated with the laser. The eye patients may also want to consult several doctors to learn about the different technologies available, so that they can make an informed choice about which option may be best for their needs. These lasers are also used in semiconductor manufacturing, materials processing, and materials marking.

The same precision which is valuable in eye surgery is also important for finely detailed manufacturing tasks. The cool aspect of the laser is also important, as it means that materials can be manipulated with minimal risk of damage.

Other types of lasers heat the material while they work, and so can lead to deformations, which compromise the integrity of the finished product.

Some of the excited dimers are: F_2, Xe_2, and some of the excited complexes *i.e*. Exciplexes are: combination of rare gas atoms like Ar, Kr, and Xe; and halogen atoms like F, Cl, and Br. The various wavelengths of the emmissions are: Ar_2 for 126 nm, Kr_2 for 146 nm, F_2 for 157 nm, Xe_2 for 172 nm and 175 nm, ArF for 193 nm, CaF_2 for 193 nm, KrCl for 222 nm, KrF 248 nm, Cl_2 for 259 nm, XeBr for 259 nm, XeBr for 282 nm, XeCl for 309 nm, N_2 for 337 nm, and XeF for 351 nm. Obviously, the wavelength of emmission depends on the the excited dimer. Also, varioius values of repetition rate from 0.05 Hz to 20 kHz, and high power ~ 10 W -200 W are obtainable; which leads to their use for the different forms of applications like – micromaching in ink jet cartidges (drilling the nozzles); radiation for changing the structure and properties of materials (active matrix LCD monitors, fiber Bragg gratings, and high temperature superconducting films); short wavelength light bulb in optical litography and computer chips, eye surgery for vision correction with ArF lasers at 193 nm, psoriasis treatment with XeCl lasers at 308 nm, and pumping dye lasers (XeCl).

C. Energy levels of excimer laser

As discussed above, the atoms result in the formation of a bound state after being raised to an ionized excited state by a high energy input, that in fact is the high laser level, from which the molecule returns to the unexcited ground state.

As the population of the lower laser level is always zero, the condition of population inversion is achieved immediately at the moment of the formation of an excited state.

The energy levels of excimer laser, as a function of the distance between the atoms in the molecule, are shown below:

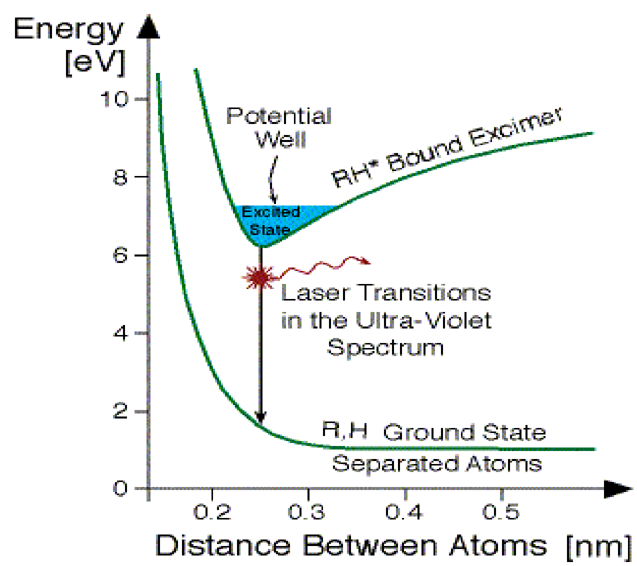

FIGURE 3. Energy levels in the excimer laser.

The parameters *R* and *H* respectively denote the noble gas atom and the halogen. It has to be noted that the valley in the form of a potential well depicts the existence of a momentary stable state; and the absence of a potential well in the ground state shows the non-existence of any bound state to the molecule when not excited. A bound state can exist only within the marked area inside the potential well of the excited state, and that too only for a specific distance between the atoms.

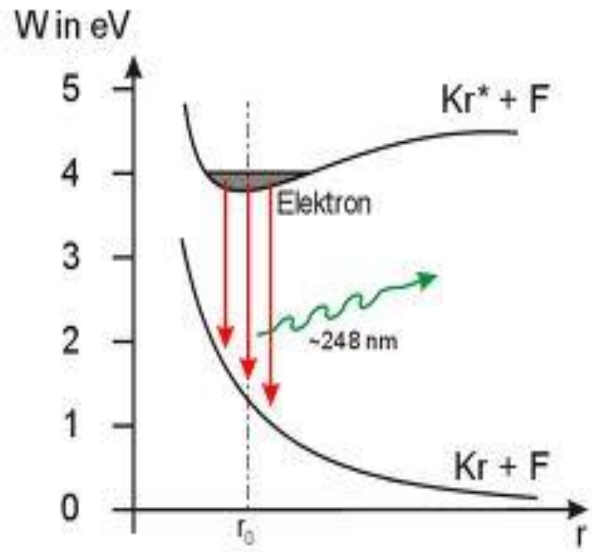

FIGURE 4. Emission of 248 nm radiation from a KrF excimer laser. Figure courtesy perg.phys.ksu.edu.

II. MATHEMATICAL CONSIDERATIONS IN THE LASER CORNEAL REFRACTIVE SURGERY

As mentioned earlier, excimer lasers have been found to be useful in the medical field of laser ablation in corneal refractive surgery [4, 5, 6, 7, 8]. Many factors influence the laser ablation and the efficiency of the outcome, including laser energy, delivery technique, ablation decentration and registration, eye tracking, flap, the physical characteristics of ablation, and the wound-healing and biomechanics of the cornea. Thus, the correction of the cornea by surgery is quite complicated, and depends on the experience and skill of the technologist doing the treatment. However, in this case, the parameter of prime importance is the thermal load ΔT of a laser pulse *i.e*. the temperature rise at the end of a laser pulse, which can be studied by following the approach [9], and is given by

$$\Delta T = \frac{\alpha}{\rho c} I(1-R), \tag{1}$$

where *I* is the radiant exposure, *R*is the reflectivity, *α* is the absorption coefficient, *r* is the density, and *c* is the specific heat. On the basis of the blow-off model derived from the Beer–Lambert law, we know that the real energy density absorbed at that point determines the ablation depth, and is given by:

$$d_{ij} = \frac{\ln[\{I_{ij}(1-R_{ij})\}/I_{Th}]}{\alpha c_{Cornea}}. \tag{2}$$

Where:

d_{ij} is the actual depth per pulse at the location *i*, *j*,
I_{ij} is the radiant exposure of the pulse at location i, *j*,
R_{ij} is the reflectivity at location i, *j*,
I_{Th} is the corneal threshold,
α_{Cornea} is the corneal absorption coefficient.

Therefore, \in general, we can write that:

$$d(r) = \frac{\ln[\{I(r)(1-R(r))\}/I_{Th}]}{\alpha c_{Cornea}}. \tag{3}$$

Which on reversing can be written as:

$$I(r)\{1-R(r)\} = I_{Th}\exp[d(r)\alpha_{Cornea}]. \tag{4}$$

Replacing this in the thermal load equation, we can write that

$$\Delta T(r) = \frac{\alpha_{Cornea}}{\rho c} I_{Th}\exp[d(r)\alpha_{Cornea}]. \tag{5}$$

While is important determining the thermal load of a refractive surgery treatment, we have to consider carefully the sequential delivery of the multiplicity of laser pulses, each one will ablat and will heat up locally a small amount of corneal tissue.

Thus, the values of *I*, *R*, *α*, have to be optimized by considering the values of *r* and *c*. Also, excited dimers, various wavelengths of the emmissions, repetition rate, and power levels have to be chosen very carefully along with the optimization of the above mentioned parameters. The values have to be very carefully computed up to the great accuracy, as in practice the response of the tissue may be slightly off the calculated value. Hence, it is a practice to be on the safe side of the computations, so as to avoid any untoward incident. Really, it is the work assigned to the skillful persons with lot of experience. Sometimes, some preliminary test is also performed for the tissue analysis of the person in consideration.

Yoon *et al.* [10] have developed a nontoric eye model, which separates the effects of differences in ablation efficiency and biological corneal surface change quantitatively and also explains how spherical aberration is induced after myopic and hyperopic laser refractive surgery.

The usefulness of this model can be judged from the fact that with the corneal topographic data, this model is being incorporated into the ablation algorithm to decrease the induced spherical aberrations, and thereby improving the outcomes of conventional and customized treatments.

Deaver *et al.* [11] have reviewed the efficacy of 308 nm excimer laser in patients with stage IA to IIA mycosis fungoides (MF), and have concluded that the use of 308 nm excimer laser in the treatment of stage IA to IIA MF shows the clinical and pathological benefit for patients with isolated lesions or lesions in areas that may be difficult to treat because of anatomic location.

The experiment has to be performed at normal incidence, and hence the need for the alignment is crucial for achieving the optimum results; as non-normal incidence affects the efficiency. Arba-Mosquera and Ortueta [12] have provided a general method to analyze the loss of ablation efficiency at non-normal incidence in a geometrical way, which is comprehensive and directly considers curvature, system geometry, applied correction, and astigmatism as model parameters, and indirectly laser beam characteristics and ablative spot properties. The technique replaces the direct dependency on the fluence by a direct dependence on the nominal spot volume and on considerations about the area illuminated by the beam.

Compensation of the loss of ablation efficiency at non-normal incidence can be made by using this model, which provides an analytical expression for corrections of laser efficiency losses, and has been found to be in good agreement with recent experimental studies, both on polymethylmetacrylate (PMMA) sheets and corneal tissue, and thus is really useful in directly improving the quality of results.

It may be noted that the excimer laser used for such purposes is a computer-controlled laser providing ultraviolet beam of light used for correcting nearsightedness. Mostly, each pulse of this laser can cut 39 millionths of an inch of tissue in 12 billionths of a second.

Before performing the surgery, a map of the eye is constructed, and the required change is then calculated and entered into the computer. Subsequently, a physician cuts a flap of tissue from the cornea, and the laser is then used to remove the specific areas of tissue from beneath the cornea, and thus resulting in the improvement of the person's eyesight. The data from the studies have shown a 95% success rate for corrective eyesight surgeries, in the sense that only 5% of persons still require glasses for distance corresponding to the perfect vision. The eye surgery for vision correction is also performed with ArF lasers at 193 nm, after correct alignment of the laser spot and making it incident on the desired point of the cornea, as shown below:

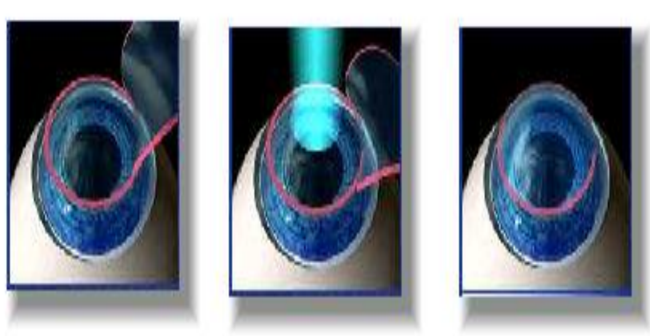

FIGURE 5. Vision correction performed with ArF lasers at 193 nm; Figure courtesy Helga Dögg Flosadóttir, Nútíma Ljósfræði, Vor 2008.

III. QUALITATIVE REVIEW OF RECENT IMPORTANT INVESTIGATIONS AND CONCLUDING REMARKS

The subject of the applications of excimer lasers has drawn the attention of various workers, and some of the important ones have been qualitatively reviewed here. Conde *et al*. [13] have presented the calculations of the temperature distribution induced by excimer lasers in silicon and germanium by using different mathematical approaches.

The heat conduction differential equation has been solved by:

(i) Conventional analytical method, where the thermal parameters like thermal conductivity, specific heat and density are temperature independent.

(ii) The Kirchhoff transformation method, incorporating the dependence of the thermal conductivity with the temperature through a polynomial function.

(iii) A numerical approach, by using the Finite Elements method, allowing the incorporation of all temperature dependent parameters and the phase changes of the material using the enthalpy function.

A comparison of the temperature profile *versus* depth obtained for semi-infinite amorphous germanium and crystalline silicon materials when irradiated with an ArF excimer laser (193 nm, 20 ns) has been presented, and the melting depth for a given energy density has been evaluated by the different mathematical methods. The validity of these results and the reliability and advantages of the numerical methods have also been discussed.

Razhev *et al*. [14] have studied the effect of the pump parameters on the efficiency of operation of a KrF gas-discharge excimer laser on a He—Kr—F_2 mixture, and have developed a theoretical model of the excitation system and the kinetic processes in the plasma of this laser. Razhev *et al*. [14] have created a pump system based on an LC inverter with a spark gap as a high-voltage switch, automatic UV preionisation, and a low-inductance discharge circuit, and have proposed the enhancement of the pump intensity to 4 MW cm^{-3} by increasing the inductance between the LC inverter and the discharge circuit to 100 nH, for increasing the efficiency and the output energy of the KrF laser based on a He—Kr—F_2 mixture. Output energy of 1 J at an efficiency of 2%, has been achieved for the first time for the KrF laser operating on this mixture. Casper *et al*. [15] have realized the spatially very homogeneous gas discharges with long-pulse duration in HCl-based rare-gas halide gas mixtures at over-atmospheric pressures, by using a low inductive three-electrode prepulse–mainpulse configuration with two discharge volumes, as excitation circuit. Very high energy transfer efficiency of the pump circuit ~ 87%, has already been achieved. Furthermore, the rise time of the discharge current has been ascertained to be very short, in order to improve the discharge stability for high pump powers. The experiments in Xe/HCl/Ne mixtures have revealed very homogeneous discharges spatially for up to 370 ns (FWHM) with a power deposition ~ 260 kW/cm^{-3}.

Also, for the case of the discharges in Kr/HCl/Ne mixtures, Casper *et al*. [15] have observed very homogeneous discharges for pump power densities > 500 kW/cm^{-3}. Interestingly, discharges in mixtures with a krypton concentration of 100 mbar and 0.5 mbar HCl are homogeneous for 300 ns, as compared to 200 ns when 1 mbar of HCl is used.

Alhowaish *et al*. [16] have reviewed all the relevant articles about 308-nm excimer laser and light sources, assessing their efficacy in the management of vitiligo (relatively common acquired disorder, characterized by progressive loss of melanocytes from the epidermis and the epidermal appendages), and also their side effects; and have analyzed the value of combination treatment methods, based on which they have concluded that the excimer laser provides the most effective approach to treat vitiligo, as compared to the ordinary phototherapy. They have discussed that the excimer laser is relatively safe and effective for localized disease, since the UV-sensitive areas respond best, and more frequent treatments achieve better results. It has been emphasized that as compared to other treatment modalities, the excimer laser most likely constitutes the treatment of choice for localized vitíligo; and its efficacy can be further improved in combination with other therapies such as corticosteroids, pimecrolimus, or tacrolimus.

Dayal *et al*. [17] have investigated the excimer laser micromachining using binary mask projection for rapid patterning of single micrometer features over large areas of various substrates, and have given the simple limit for depth of focus that determines the depth to width aspect ratios, and verified it for different materials. For this study, the binary mask projection technique has been found to conformally reproduce the mask features from the millimetre to the micrometer scale under proper focusing conditions. Large arrays of 1 μm and 15 μm holes on Kapton have been made with high resolution and uniform periodicity. Besides, the material removal rates for the laser machining of these holes have been examined, and the machining efficiencies for these have been found to have different dependences on the fluence. Tanawuttiwat *et al*. [18] have studied and discussed the results of their study on lead extraction experience with high frequency excimer laser in detail. Danilychev [19] has presented a brief review of the first experimental papers on the generation of powerful pulsed VUV radiation, when it is excited by a relativistic electron beam in inert gases in the solid, liquid, and gaseous states in the temperature range 58–300 K, and has considered the details of the experimental technique, besides presenting the results of the experiments on the generation of powerful spontaneous and stimulated VUV radiation. It has been emphasized that these studies have led to the development of the xenon-dimer laser.

Liu *et al*. [20] have discussed the 193 nm ArF excimer laser micromachining on five representative micro-electro-mechanical systems (MEMS) materials (Si, soda-lime glass, SU-8, polydimethylsiloxane (PDMS), and polyimide), and have investigated the relations between laser parameters (fluence, frequency and number of laser pulses) and etch performances (etch rates, aspect ratio, and surface quality). It has been observed that:

(i) The etch rate per shot is proportional to laser fluence but inversely proportional to the number of laser pulses, and is quite independent of the laser frequency.

(ii) The aspect ratio is also proportional to laser fluence and number of laser pulses but is not affected by laser frequency.

Interestingly, the materials absorbance spectrum is found to have important influence on etch rates. Thermal properties of material, primarily thermal conductivity, have also been observed to have significant influence on etching results.

The 3D microfabrication capability of ArF excimer laser, has also been demonstrated by successfully cutting and local removing of insulation for a novel floating braided neural probe made of polyimide and nichrome, using the optimized laser ablation parameters.

High pulse energy excimer lasers with photon energies ~ 7.9 eV have been reported to be very useful for the technique of pulsed laser deposition since virtually every target material is amenable to excimer laser ablation and its subsequent stoichiometric transfer to a substrate, and thus provides maximum flexibility. Importance and the novel applications of the excimer lasers have led to large research and development programs by the commercial firms.

Herbst [21] has discussed that the excimer lasers are key to the low-temperature annealing of polycrystalline silicon for the volume production of flat panel displays. It is interesting to observe that the manufacturers have responded to the needs of this application by developing a new generation of industrial excimer lasers, which offer the necessary combination of high pulse energies and high energy stability. It may therefore be concluded that the subject of the excimer lasers and their applications, especially in eye surgery, is on a firm footing, and evolving fast.

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