Large-Area Surface Discharge UV Light Source for Materials Processing Applications

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Abstract

Performance of a 6"X 6" surface discharge that give integrated light intensities greater than 400 mJ/cm² is reported here. Light uniformity on the surface of high density alumina dielectric has been measured to show better than 5% across the entire discharge area. Detailed spectroscopic content of these discharges in different gases and gas mixtures are presented from 160nm to 735nm region.

Introduction

Recently¹ fairly large surface discharge areas have been excited uniformly for the initiation of chemical lasers. The possibility of extremely uniform large area ultraviolet sources suggests the use of these incoherent sources for materials processing. The UV energy density required for materials processing in a number of applications generally must exceed 300 millijoules/cm². We have constructed a surface discharge of 6"x6" (15.24cm X15.24cm) dimension to study the scaling issues. Our device has produced some 400 mJ/cm² of integrated light from the 200-800nm region in krypton buffer. Detailed spectroscopic studies from 160-735nm have shown that in argon 46% of the measured light is in the 160-360nm region and 26% in the 200-360 nm region and in krypton 49% of the measured light is in the 160-360 nm region with 30% in the 200-360nm region. The total integrated light in krypton is some 1.4 time that in argon. From these results we obtain energy density in the 200-360 nm region to be 74 mJ/cm² in argon and 120 mJ/cm² in krypton. This is a factor of nearly 5.4 for argon and a factor of 3.3 for krypton too low before the device reach threshold energy densities useful for single shot annealing type of processing applications of materials and thin film surfaces. The best UV generation efficiency we obtained in the 200-360 nm region is .9% of the stored energy (3.1KJ at 40KV). This is a factor of 9 lower than the 8% we had hoped for as reported in the literature for much narrower and, therefore, higher resistance surface discharges.

Apparatus

The design of the device was driven by two considerations. First is all materials be free from carbon formation that could potentially contaminate the material to be processed. This eliminates all fluorocarbon and chlorocarbon materials such as teflon and kynar which are rather ideal materials because of their high dielectric strength and reasonable dielectric constants and because they can withstand strong mechanical shocks. Second is to make the design compatible

with the use of very brittle ceramic or glass materials of very large dimensions that must be used as the dielectric. Such a design must be compatible with scaling the device at a minimum to dimensions of present day lap top computer liquid crystal displays.

A schematic of the device is shown in Fig. 1. Incorporating

Figure 1. Schematic of large area surface discharge source.

porating high gas flow rates across the dielectric surface as well as 20 kilowatts of cooling into the design allow for eventual moderately high repetition rate operation. The pulse power design discussed in this paper is for low repetition rate operation (< .1Hz). The dielectric plate is placed on top of the ground return plate and held in place only by pressing the electrodes tightly on the plate and tightening lockdown screws. This technique holds the dielectric by compressive forces only and allows the plate to freely move laterally during the discharge time when substantial shockwaves are created. The major controlling factors of the surface discharge area are the electrode separation and the width of the ground return plate. We find that if we use electrodes of smaller width, the discharge rapidly fills to the width defined by the ground return plate at fairly short distances from the electrode.

Figure 2 gives the schematic of the pulse power circuit. The circuit is composed of three independent charge transfer units to reduce the peak current in each of the three spark gaps (Maxwell Model 40044, 50KV, 50KA). All three spark gaps are triggered by a single high voltage trigger source fed through separate coaxial cables. Each circuit contains 1.4 μF storage capacitance using two Maxwell Laboratory (Model 31161, 0.7mF, 17-25nH, 50KV, 25KA) capacitors. A 40KV, 60 mA source serves as the D.C. charging

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power supply and charges the main capacitors through charging resistors and isolation resistors as indicated in the

Figure 2. Schematic of pulse power circuit.

diagram. The main capacitor are charged negatively to make uniform surface discharge initiation easier.

For impedance matching between a low surface discharge resistance and the excitation circuit, the output inductance of the excitation is designed to be as low as possible. By placing the circuits in transformer oil, the parallel conductor plates between the main capacitor and the discharge electrodes could be minimized to lower circuit inductance. Stainless steel is used for the main electrodes to minimize erosion by the high density discharge current.

Surface Discharge Uniformity

We have measured the surface discharge uniformity by looking at the visible light using a CCD camera focussed onto the top surface of the dielectric. Neutral density filters and aperture adjustments were made to bring the light levels down to regions where the fine structure of the discharge can be observed. Analysis are performed using the Beamcode™ program by Big Sky. We find the discharge on high density alumina plate to be extremely uniform and that on plate glass plate to be substantially worse.

Figure 3. 3-Dimensional Beamcode™ display of surface intensity on 1/8" thick alumina plate in 500 Torr argon buffer gas at 30KV charging voltage.

Figures 3, 4 and 5 give typical light flux measurements on the high density alumina surface (1/8" thick) in three-dimensional display, two-dimensional surface intensity

Figure 4. Two dimensional Beamcode™ display with color correlated intensity variation display on 1/8" thick alumina plate in 500 Torr argon buffer gas at 30KV charging voltage.

Figure 5. Histogram display (Beamcode™) of intensity variation across whole discharge surface area on 1/8" thick alumina plate in 500 Torr argon buffer gas at 30KV charging voltage.

display (to show to fine grain multiple arcs of the discharge) and the histogram of the surface intensity across the whole lighted surface area, respectively. This data was taken in 500 Torr of Argon and 30KV charging voltage. Similar results

are observed at higher pressures and higher voltages. Fig. 5 calculates the uniformity across the whole surface to be better than 5% where the uniformity is defined as $\Delta I/I_{\text{PEAK}}$ with ΔI , the intensity at half maximum of the maximum pixel count and I_{PEAK} , the intensity at the maximum pixel count. We found also the high density alumina delivered to us to be inconsistent in density from batch to batch (a set of plates ordered at a different time from the same vendor did not even stand-up to the discharge from the trigger pulser of the spark-gaps).

Discussion of Light Uniformity at the Processing Plane

We see from the last section the existence of fine streamers in the surface discharge. Even at short processing plane distances from the source plane these intensity non-uniformities should wash out. It is important, however, in many applications that the radiant intensity on the whole surface of the material to be processed be uniform within a certain percentage of the peak intensity. For these reasons we wish to calculate the intensity distribution an arbitrary distance away from a rectangular or square emitting surface. We can assume Lambertian emitters for each emitter element on the dielectric surface. At one normalized distance away from the surface (a distance equal to the linear dimension of a square emitter) Figure 6 shows the intensity has decreased by a factor of 5 of the intensity generated at the surface.

Figure 6. Intensity distribution as a fraction of the radiation intensity at 1 normalized distance from the source plane.

Figure 7 plots the intensity, normalized to a fraction of the surface intensity, at given distances away from the surface discharge as a function of the x-axis for the center of the y-axis. These calculations also allow us to make simple energy measurements a given distance from the surface using energy meters. Figure 8 shows this measurement in argon buffer as a function pressure and charging voltage. These measurements

were performed with the energy meter in air and, thus, is

Figure 7. Normalized intensity as a fraction of source plane intensity density at the center of the y-axis.

Figure 8. Spectrally integrated light intensity measured through calcium fluoride window. Energy measurement corrected for distance energy meter is from source. Data taken as function of charging voltage and argon pressure.

limited by the Schumann-Runge absorption band of oxygen. The energy is, therefore, the integrated light flux from 200-800nm. Integrated light energies of 275 mJ/cm² are obtained. The light energy increases much more dramatically as a function of pressure than of charging voltage. An illustration that differences between the spark gap and the surface discharge is playing a more important role than stored energy in the creation of the intense light flux.

Detailed Spectroscopic Studies

The data presented have been background adjusted and corrected for instrumental distortions. Figure 9

Figure 9. Instrumental distortion corrected surface discharge flash spectra of helium, neon, argon, and krypton at 1000 Torr with charging voltage=30 KV.

gives the complete surface discharge spectra for helium, neon, argon and krypton at 1000Torr filling pressure and 30KV charging voltage (1890 Joules stored). Observe that not only do we see a gradual continuous rise in the UV (broadband blackbody radiation?) but there is very substantial line spectra content in the regions below 180nm. Viewing the spectral content of the different gases, it is easy to see certain lines that are common to all the gases and these are assumed to come from elements of the dielectric. Note, for example, the line slightly to the short wavelength end of 660nm. In particular we observe the very strong emission in krypton, argon and helium buffers but fairly weak in neon at 167nm. This is

extremely strong in these gases and contribute substantially to the vacuum UV content. We identify this line as the $3p\ ^1P^o_0 - 3s\ ^2S_0$ transition of singly ionized aluminum. In helium based mixtures a very strong transition is observed at 164.3nm. No known transition in helium match this state. Adding this photon energy to the first excited state of helium result in an energy level beyond the dissociation limit. Transitions from impurities such as silicon or oxygen does not match this very strong line. Presently, we believe this to be an autoionizing transition in helium from the first excited state (2^3S_1).

Light Production and Discharge Parameters

The spectroscopic data show strong increases in light output across the whole spectrum measured as a function of increasing pressure as shown in Fig. 10. This is judged to be

Figure 10. Flash spectra comparison in argon buffer at three pressures 1000, 750 and 500 Torr on alumina dielectric. Charging voltage=30KV.

directly correlated to the fraction of stored energy deposited in the surface discharge. The distribution of energy deposition is divided between the surface discharge and the three triggered spark gaps in series with the discharge. Knowledge of the resistances of the spark gaps and of the surface discharge can be obtained through voltage current measurements and through the spectroscopic studies and their relationship to deposited energy.

Typical voltage and current waveforms are shown in Fig. 11 including the temporal behavior of spectrally integrated light output as detected with a PIN photodiode. The total circuit resistance is calculated from the damping ratio of the current. The discharge resistance is assumed constant during the period from the first to the second peak of the current pulse. MICRO-CAP IV (Spectrum) circuit analysis software is used to derive inductive and resistive parameters for the pulse power circuit to give temporal voltage and current behavior in agreement with our measurements. This analysis gives the discharge resistance ($R_{disch.}$) including the spark

gaps switch and the surface discharge ($R_{sd} + R_{sg} = R_{disch.}$) = 0.09Ω at a charging voltage of 30KV and an argon pressure of 500 Torr where a $1.5\mu s$ long (a half cycle of a sine wave)

(a)

(b)

Figure 11. Typical voltage, current and fluorescence temporal waveforms of surface discharge

current pulse with a peak of about 70 KA per circuit is measured. The current pulse duration is defined as the duration from the onset to the inversion of the current. The total stored energy in the main capacitors is 1.9 KJ. The total inductance of each circuit is 160 nH. The surface discharge resistance in this particular case is estimated at the peak of the current. The instantaneous V/I value across the surface discharge, thus, gives an $R_{sd}=0.0257\Omega$. From this result we can obtain a value for the resistance of the three spark gaps in parallel as $R_{sg}=0.0643\Omega$. We will assume that as long as the spark gap pressures are nominally of the same value, this result for the spark gap resistance is valid in the following discussion. The UV light production as a function of deposited energy has been measured¹ and show a square dependance. Figure 12 gives the measured light intensity as a function argon pressure at a number of wavelengths as obtained from Fig. 10. Using,

$$E_{\text{emission}} \propto E_{\text{deposited}}^2$$

and

$$E_{\text{deposited}} = [R_{sd}/(R_{sd}+R_{sg})]E_{\text{stored}}$$

we can obtain the surface discharge resistance at each pressure assuming the spark gap resistance remains constant. The data shows that even at the highest pressure used in these measurements, the surface discharge resistance is less than the spark gap resistance so that less than half the stored energy is deposited into the surface flash.

Figure 12. Normalized emission intensity (normalized to data at 1000Torr) at selected wavelengths in argon buffer and estimated surface discharge resistances as a function of pressure.

Discussion

Figures 13 and 14 give the fractional energy content as a function wavelength for various argon pressures and for

Figure 13. Integrated fractional energy content starting at 760 nm as a functional of wavelength (normalized to total energy of 1 for 1000torr argon) for different filling pressures.

different buffer gases all normalized to the data of argon buffer at 1000Torr. This compilation shows that krypton gives total integrated light intensities a factor of 1.4 higher

Figure 14. Integrated fractional energy content starting at 760 nm as a functional of wavelength (normalized to total energy of 1 for 1000torr argon) for different buffer gases including helium, neon, argon and krypton.

References:

1. G.P. Quigley, R.F. Harrison and T. Shimada, "Surface discharge pumped chemical lasers," Conference on Lasers and Electro-optics, Technical Digest paper CTHB2, Baltimore, MD. (May 1993)

than that of argon. Coupled with the direct measurements of Fig.8, we obtain 400 mJ/cm^2 of integrated light from the 200-800 nm region in krypton buffer. The percentage of this energy in the 160-360nm UV region is measured to be 48.7% and in the easily accessible 200-360nm region to be 30%. In argon buffer the light content in the 160nm-360nm constitute 46% of the integrated light and in the 200-360nm region constitute 26% of the integrated light. This translates to energy content in the 200-360nm region of 74 mJ/cm^2 in argon and 120 mJ/cm^2 in krypton. This is a factor of 5.4 for argon and 3.3 for krypton too low for materials processing applications involving the melting of thin film materials. The best UV generation efficiency we obtained in the 200-360 nm region is .9% of the stored energy (3.1KJ at 40KV). This is a factor of 9 lower than the 8% we had hoped for as reported in the literature for much narrower, higher impedance surface discharges.

Figure 1

Pulsed Power Circuit Diagram for a Surface Discharge Pumped VUV Light source

Figure 2

Three Dimensional Beamcode™ Display of the Surface Intensity with an Alumina Plate (Thickness : 1/8")

Figure 3

Beamcode™ Display of the Surface Intensity with an Alumina Plate (Thickness : 1/8")

COLOR TABLE

16 Levels

145-155→

136-144→

126-135→

116-125→

107-115→

97-106→

87-96→

78-86→

68-77→

58-67→

48-57→

39-47→

29-38→

19-28→

10-18→

0-9→

ANODE

Contouring Mode = Automatic Scaling

CATHODE

Histogram of of the Surface Intensity Variation With an Alumina Plate (Thickness : 1/8")

<Intensity>	
MAX Intensity =	155
MIN Intensity =	0
AVG Intensity =	130
STD Deviation =	24
MAX Pixels =	6978 @ Int 134
MIN Pixels =	0 @ Int 5

<Region of Interest>	
TYPE:	ENTIRE ARRAY

<Cursor Data>			
Int	Pixels	%Eng	
I1 131	2945	5.169	
I2 138	3673	6.792	
ΔI 7	40217	72.501

$$\text{Discharge Surface Uniformity} \left(\frac{\Delta I}{I_{\text{PEAK}}} \right) = 5\%$$

Figure 5

INTENSITY DISTRIBUTION 1 NORMALIZED DISTANCE FROM SOURCE

Figure 10

NORMALIZED INTENSITY DISTRIBUTION AT CENTER OF Y-AXIS

Figure 14

LIGHT ENERGY ON SLIDING DISCHARGE SURFACE MEASURED THROUGH CALCIUM
FLUORIDE WINDOW AS FUNCTION OF CHARGING VOLTAGE FOR VARIOUS PRESSURES OF
ARGON

(a)

(b)

Figure 28

Flash Spectra Comparison of Argon at three pressures 1000, 750 and 500 Torr, Charging Voltage=30KV on Alumina (Instrument Corrected Spectra)

Figure 29

Fractional Energy Content as a Function of Wavelength at Different Pressures of Argon
(Normalized to Argon Fill at 1000Torr, Charging Voltage=30KV)

Fractional Energy Content as a Function of Wavelength Normalized to Data of Argon (all Gases at 1000Torr and Charging Voltage of 30KV)