Design and Fabrication of Atmospheric Pressure Microglow Discharges for Low-Cost UV Lamps

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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Design and Fabrication of Atmospheric Pressure Microglow Discharges for Low-Cost UV Lamps

by

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in fulfillment of the requirement of the degree of Doctor of Philosophy
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In loving memory of my dear late Khaala, Baji,
whose presence remains deeply cherished
and
dedicated to my beloved parents,
grandparents, and my wonderful brothers, whose unwavering support has been my greatest strength throughout this journey.

Certificate

This is to certify that the thesis entitled **“Design and Fabrication of Atmospheric Pressure Microglow Discharges for Low-Cost UV Lamps”** being submitted by **Ms. Rumysa Manzoor** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by her worked under my guidance and supervision and fulfilled the requirements for the submission of the thesis. The results contained in the thesis have not been submitted, in part or full, to any other university for the award of any degree or diploma.

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Place: New Delhi

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By studying the matter at the micro and nano level, I not only gained a deeper understanding of devices at such scales, but it also deepened my faith. It reminded me of the profound truth in the words of Allah (SWT) in Surah Yunus (10:61):
"And not [even] the weight of a dust particle in the earth or in the heaven is absent from your Lord, nor anything smaller than that or greater, but it is in a clear Record."

This verse beautifully affirms that even the tiniest details are known to our Creator, a realization that resonated with me throughout this journey of learning.

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This institute did not just teach me science; it became a guiding light, showing me how to navigate life itself. My time here offered a glimpse into how to face both the highs and the lows with resilience and purpose.

Like any other Ph.D. scholar, my journey was far from smooth. It was marked by more failures than successes. But those very failures taught me lessons that success never could. They reminded me that there is always light at the end of the tunnel and brought to mind a powerful ayah from the Qur'an: “Indeed, with hardship comes ease.” (Surah Ash-Sharh, 94:6)

But often, we become so engrossed in our hardships that we fail to recognize the blessings hidden within them. We overlook how these challenges shape us, how they teach us resilience, nurture patience, and mould us into more compassionate human beings. Had this journey not been so difficult, I would not have discovered the strength within me. I would not have become the person I am today, nor would I have truly understood how resilient I could be. This journey tested my patience in countless ways and across different aspects of life. But I never let go of

the urge to live my life in harmony with those around me, and to continue moving forward with hope and purpose.

Being away from home, I lost two of my close family members. I could not be there for them in their final moments, the way they would have expected me to. But as I complete my thesis today, I carry the hope and belief that they would be proud of me.

I am truly thankful to all the beautiful souls I met along the way. From the very first day of my Ph.D., there was a close-knit squad of friends who made this journey feel like home. I will always cherish the unwavering support of my dear friends, Dr. Sobia, Dr. Sharaf, Dr. Sushree, and Ms. Kritika. You were always there with me, whether it was waking each other up for breakfast or walking back together from the labs or those unforgettable bicycle learning sessions. These shared moments became my anchor, my comfort, and a source of strength throughout this journey.

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and integrity of my father continue to inspire me every single day. May the mercy of Allah (SWT) surround them and grant me the ability to honour them always.

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This Ph.D. journey has been nothing short of a roller coaster, filled with challenges, lessons, and growth. But in the end, it became one of the greatest teachers and mentors of my life. I would have missed the most important lessons had I not chosen this path.

Rumysa Manzoor

Abstract

The primary objective of our work is the research and development of high-pressure microplasma devices as a compact and efficient ultraviolet (UV) lamp suitable for advanced optical applications. High-pressure microplasma offers significant benefits, including enhanced excimer emissions and elevated electron densities. As such, these devices are emerging as promising candidates for next-generation UV radiation sources. However, maintaining stable plasma operation at elevated pressures poses some peculiar challenges, including the potential for glow-to-arc discharge transitions and electrode degradation. Furthermore, encapsulating these devices with a UV-transparent thin film is implemented using sol-gel films that are optimized for optical transparency and mechanical robustness.

In this research, thick electroplated copper electrodes fabricated using the UV-LIGA process are utilized to investigate the performance of high-pressure microplasma devices. A pulsed DC power supply is used to maintain a stable glow discharge at high pressures. The formation of Argon excimer enhances UV emission. Excimer formation is a three-body reaction and is enhanced at higher pressures. With this view, the characteristics of discharges at higher pressures are investigated. We show that microplasmas can achieve consistent performance up to 2 atm with optimized geometries.

Plasma inside nanoporous channels is investigated for increasing the device longevity and reducing electrode degradation. It is observed that nanoporous electrodes not only increase longevity, but they also result in high plasma density, temperature, and more stable plasma discharges.

A novel micro-shell packaging approach is introduced to tackle the challenge of UV-transparent encapsulation. A process of fabricating a UV-transparent porous silica cap, synthesized via a sol-gel method at low thermal annealing temperatures, is developed and optimized. The process is optimized for both porosity and UV transparency, leading to an encapsulation that ensures minimal optical loss while providing adequate structural integrity. This balance between porosity and optical transmission is critical for the successful packaging of microplasma devices. A controlled pore distribution of porous silica film is achieved, which facilitates 55 % UV transparency. Further, the pores in the encapsulation act as natural etch-release holes, simplifying one of the most complicated steps of the fabrication process.

Overall, this research aims to develop a stable, high-pressure microglow discharge device with enhanced durability and minimal electrode degradation. The findings highlight that by integrating thick-film copper electrodes, nanoporous materials, and UV-transparent encapsulation, a scalable solution for reliable, high-performance microplasma-based UV lamp devices can be developed. The robust and scalable fabrication strategies developed herein may find application in environmental sensing, water purification, and other applications requiring reliable, high-performance UV sources.

सार

हमारे कार्य का मुख्य उद्देश्य उच्च-दाब माइक्रोप्लाज्मा उपकरणों का अनुसंधान और कॉम्पैक्ट और कुशल पराबैंगनी (यूवी) लैंप का विकास करना है, जो उन्नत ऑप्टिकल अनुप्रयोगों के लिए उपयुक्त हो। उच्च-दाब माइक्रोप्लाज्मा कई महत्वपूर्ण लाभ प्रदान करता है, जिनमें उच्च एक्साइमर उत्सर्जन और बढ़ी हुई इलेक्ट्रॉन घनता शामिल हैं। इस कारण, ये उपकरण अगली पीढ़ी के यूवी विकिरण स्रोतों के लिए एक संभावित समाधान के रूप में उभर रहे हैं। हालांकि, उच्च दाब पर स्थिर प्लाज्मा संचालन बनाए रखना कुछ विशेष चुनौतियाँ उत्पन्न करता है, जिनमें ग्लो-टू-आर्क डिस्चार्ज संक्रमण और इलेक्ट्रोड क्षरण की संभावना शामिल है। इसके अतिरिक्त, इन उपकरणों को सोल-जेल विधि के द्वारा पतली पारदर्शी अल्ट्रावायलेट फिल्म से संलग्न किया गया है, जिसे ऑप्टिकल पारदर्शिता और यांत्रिक मजबूती के लिए अनुकूलित किया गया है।

इस शोध में, उच्च-दाब माइक्रोप्लाज्मा उपकरणों के प्रदर्शन का अध्ययन करने के लिए यूवी-लीगा प्रक्रिया द्वारा निर्मित मोटे इलेक्ट्रोप्लेटेड तांबे के इलेक्ट्रोड का उपयोग किया गया है। उच्च दाब पर स्थिर ग्लो डिस्चार्ज बनाए रखने के लिए स्पंदित डीसी पावर का उपयोग किया गया है। आर्गन एक्साइमर के निर्माण से यूवी उत्सर्जन में वृद्धि होती है। एक्साइमर निर्माण एक त्रिकाय प्रतिक्रिया है, जो उच्च दाब पर अधिक प्रभावी होता है। इसी दृष्टिकोण से, उच्च दाब पर डिस्चार्ज की विशेषताओं की जाँच की गई है। हमने दर्शाया कि अनुकूलित ज्यामिति द्वारा माइक्रोप्लाज्मा 2 वायुमंडलीय दबाव तक स्थिर प्रदर्शन प्राप्त कर सकता है।

नैनोपोरस (सूक्ष्म-छिद्रित) चैनलों के अंदर प्लाज्मा का अध्ययन किया गया ताकि उपकरण की दीर्घायु बनाया जा सके और इलेक्ट्रोड के क्षरण को कम किया जा सके। यह देखा गया कि नैनोपोरस इलेक्ट्रोड न केवल दीर्घायु बना बनाते हैं, बल्कि उच्च प्लाज्मा घनत्व, तापमान और अधिक स्थिर प्लाज्मा डिस्चार्ज भी प्रदान करते हैं।

यूवी -पारदर्शी संलग्नकरण की चुनौती को हल करने के लिए एक नवीन माइक्रो-शेल पैकेजिंग विधि प्रस्तुत की गई है। निम्न तापमान पर सोल- जेल विधि द्वारा संश्लेषित एक यूवी -पारदर्शी

छिद्रपूर्ण सिलिका कैप निर्माण विधि विकसित और अनुकूलित की गई है। इस प्रक्रिया को छिद्रता और यूवी पारदर्शिता के लिए अनुकूलित किया गया है, जिससे न्यूनतम ऑप्टिकल हानि के साथ-साथ पर्याप्त संरचनात्मक मजबूती सुनिश्चित की जा सके। छिद्रता और ऑप्टिकल संचरण के बीच संतुलन माइक्रोप्लाज्मा उपकरणों की सफल पैकेजिंग के लिए महत्वपूर्ण है। इस प्रक्रिया में नियंत्रित छिद्र वितरण प्राप्त किया गया, जिससे 55% यूवी पारदर्शिता प्राप्त हुई। इसके अतिरिक्त, संलग्नकरण में मौजूद छिद्र प्राकृतिक निक्षारण विमोचन छिद्र के रूप में कार्य करते हैं, जिससे निर्माण प्रक्रिया के सबसे जटिल चरणों में से एक को सरल बनाया जा सका है।

समग्र रूप से, इस अनुसंधान का उद्देश्य एक स्थिर, उच्च-दाब माइक्रोग्लो डिस्चार्ज उपकरण विकसित करना है, जो अधिक टिकाऊ हो और जिसमें इलेक्ट्रोड क्षरण न्यूनतम हो। इस अध्ययन से यह स्पष्ट होता है कि मोटे-फिल्म तांबे के इलेक्ट्रोड, नैनोपोरस सामग्री और यूवी -पारदर्शी संलग्नकरण के संयोजन से एक विश्वसनीय, उच्च-प्रदर्शन माइक्रोप्लाज्मा-आधारित यूवी लैंप उपकरण के लिए एक स्केलेबल समाधान विकसित किया जा सकता है। इस अनुसंधान में विकसित मजबूत और स्केलेबल निर्माण रणनीतियाँ पर्यावरणीय संवेदन, जल शुद्धिकरण और अन्य उच्च-प्रदर्शन यूवी स्रोतों की आवश्यकता वाले अनुप्रयोगों में उपयोग की जा सकती हैं।

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List of Abbreviations

OH	Hydroxyl
AC	Alternating current
AFM	Atomic Force Microscopy
AAO	Anodic Aluminium Oxide.
APM	Atmospheric pressure microplasma
APPS	Atmospheric pressure plasmas
APT	Advanced Process Technology
Ar I	Argon
AR II	Ionized argon
ASIQ	Alpha-Step IQ Surface Profiler
BSG	Borosilicate glass wafer
C2H5OH	Ethanol
Cu	Copper
d	Interelectrode spacing
DBD	Dielectric Barrier Discharge
DC	Direct current
DI	Deionized
DMSO	Dimethyl sulfoxide
DSA	Drop Shape Analyser
DUV	Deep ultraviolet
DUT	Device under test
EDAX	Energy dispersive X-Ray Spectroscopy
EDS	Energy dispersive X-Ray Spectroscopy
eV	Electron volt
FESEM	Field emission scanning electron microscopy
GPa	Giga Pascal
H_2SO_4	Sulfuric acid
H_2O_2	hydrogen peroxide
HCl	Hydrochloric acid
HNO_3	Nitric acid
IPA	isopropyl alcohol

KPM	Kelvin probe microscopy
LIGA	Lithography, Electroforming, and Moulding
LIMO	A push-pull high precision connector
$Mg(OC_2H_5)_2$	Magnesium ethoxide
MEMS	Microelectromechanical systems
MOSFET	Metal-oxide-semiconductor field-effect transistor
N_2	Nitrogen
NIST	National Institute of Standards and Technology
OES	Optical emission spectroscopy
p	Gas pressure
PCB	Printed circuit boards
pd	Product of pressure and interelectrode distance
PDMS	Polydimethylsiloxane
PID	Photoionization detectors
PRV	Pressure release valve
PS	Polystyrene
PVA	polyvinyl alcohol
PXRD	Powder X-ray diffractometer
rpm	Rotation per minute
SCCM	Standard Cubic Centimetres per Minute
SEM	Scanning electron microscopy
SiO2	Silica
SPV	Surface photovoltage
T_0	Time duration from the start of the reaction to the time of coating
T_1	Annealing time
Te	Electron temperature
TEOS	Tetraethyl orthosilicate
TFA	Trifluoroacetic acid
Ti	Titanium
ULSI	Ultra-large-scale integration
UNHT	Ultra-nano hardness tester
UV	Ultraviolet
UVC	Ultraviolet-C
Vbmin	Minimum breakdown voltage

VPP	Peak-to-Peak Voltage
VOC	Volatile organic compounds
VUV	Vacuum ultraviolet
WPE	Wall-plug efficiency