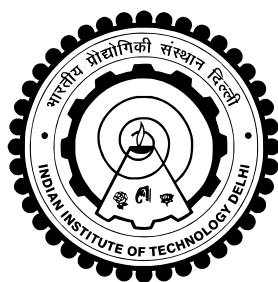


SOLUTION-PROCESSED NEAR-INFRARED (NIR) DETECTORS

Nidhi Dua



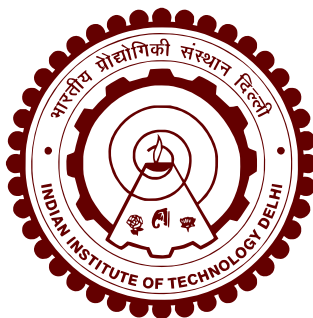
**Department of Electrical Engineering
Indian Institute of Technology Delhi
May 2025**

©Indian Institute of Technology Delhi(IITD), New Delhi, 2025
All rights reserved.

Solution-processed near-infrared (NIR) detectors

Nidhi Dua

A dissertation submitted in partial fulfilment of conditions
for award of the degree of Doctor of Philosophy



Department of Electrical Engineering
Indian Institute of Technology Delhi
May 2025

Copyright © 2025 Nidhi Dua All Rights Reserved, except for any material that may be clearly marked and attributed to external sources. In those cases alone, the copyrights pertaining to the identified material belong to their respective owners.

Use of the material herein is protected by Indian Copyright Act, 1957 (and any subsequent Amendments), and applicable International copyright Treaties that India is signatory to. "Fair Use" and "fair dealing" is permitted within the context of widely accepted academic standards, subject to legal interpretation in Indian courts.

The author(s) hereby grant(s) to IIT Delhi permission to reproduce, and to distribute publicly, paper and electronic copies of this document using any medium now known, or hereafter created, subject to conditions of the copyright, and reproduction of this notice.

Certificate from Advisor

This is to certify that the thesis entitled **Solution-processed near-infrared (NIR) detectors**, being submitted by **Nidhi Dua** to IIT Delhi, is worthy of consideration for the award of the degree of Ph.D. and is a record of the original research work carried out by this student under my supervision. The results contained in this thesis, which may have been previously communicated in the form of manuscripts, conference presentations or patent filings, have not been submitted in part or full, to any other University or Institute for the award of any academic degree.

I certify that this student has pursued the prescribed course of research.

Research Advisor:

Madhusudan Singh

Acknowledgements

I am extremely thankful to my supervisor, Prof. Madhusudan Singh, for his constant support and encouragement during both the tough and rewarding phases of my Ph.D. journey. Working under his mentorship has been beneficial to my professional growth, and I am grateful for the opportunities to learn and develop my skills. I want to thank the chair of my committee, Prof. Bhaskar Mitra, Prof. Abhisek Dixit, and Prof. Samaresh Das for their patience and feedback, and for generously sharing their knowledge and expertise. Furthermore, I must extend my gratitude to the University Grants Commission, UGC for their financial support, which made this research endeavor possible. I must thank the Department of Electrical Engineering staff for assisting me with all of the paperwork for attending international conferences, etc. I would also express my gratitude to the managing staff at CRF and NRF.

I would like to thank my FMDL labmates, Dr. Rajinder Singh Deol for successful fabrication of my devices in University of Ottawa, Canada under supervision of Prof. Ghassan E. Jabbour, and Dr. Nitika Batra for assistance with the mask design and writing. A huge thanks to the postdocs of our lab, Dr. Meenal Mehra, Dr. Soumen Saha, Dr. Sandeep Kumar, Dr. Henam Sylvia Devi, Dr. Md. Samim Hassan for helping me in my synthesis experiments. I am grateful to Mr. Parvez Akhtar for lending me his photodetector, and for generously giving up his valuable time in carrying out painstaking measurements even though he was busy with his own doctoral work. Our mutual discussions helped me come to the conclusions of my work. My other FMDL colleagues, Md. Samim Raza, Mr. Tejveer Anand, were also helpful for offering useful insights in my optical experiments directly or indirectly. I am immensely grateful to Prof. Suddhasatwa Basu (Dept. of Chemical Engineering) and his Ph.D. students for supporting me during the early stages of my PhD when I had no facilities to conduct experiments. I also want to thank Prof. Sameer Sapra (Dept. of Chemistry), Prof. Ravi Shankar (Dept. of Chemistry), Prof. Joby Joseph (Dept. of Physics), and lab assistants, Mr. Virani (MTech Physics Optics Lab), Mr. Vijay (Physics Optics Lab), Ms. Neeru Asija (Optical Communications Electrical lab) for providing access to their tools/ chemicals etc. whenever needed.

Lastly I would be remiss if I didn't mention the role that my family has played throughout this journey – my parents, in-laws, siblings, spouse. Their unwavering belief in me has kept me motivated and uplifted, during every step of this process. I am grateful to God for blessing me with my child, Ruhani, who has brought immense joy to my life.

Abstract

Near-infrared (NIR) detectors using upconversion materials are a promising technology for various applications, including imaging, sensing, and communication. Upconversion materials are typically used to convert longer-wavelength NIR photons into shorter-wavelength visible or ultraviolet photons, which can be easily detected using conventional photodetectors like silicon-based photodiodes. This upconversion process allows for the efficient detection of NIR light, which is otherwise challenging to detect directly with traditional detectors. This process involves the lanthanide-doped crystals or nanoparticles that can absorb multiple low-energy NIR photons and combine their energy to emit a single higher-energy photon in the visible or ultraviolet range. This process is often called anti-Stokes or upconversion luminescence. When NIR light (typically in the range of 700 nm to 1700 nm) is incident on the upconversion material, it is absorbed by the lanthanide dopants. The energy from multiple absorbed NIR photons is combined to promote an electron to a higher energy level. The excited electron eventually relaxes to its ground state by emitting a higher-energy photon in the visible or ultraviolet range. The emitted photon is then detected using a conventional photodetector.

Upconversion Material Synthesis and Analysis: This dissertation focuses on the synthesis of upconversion material, $\text{NaYF}_4\text{:Yb, Er, Gd}$ through thermal decomposition method for retrofitting its thin layer on Si-based detectors. The study establishes the optimal annealing conditions for this important photonic material for potential detectors. The material is synthesized at 320°C to obtain the nearly pure hexagonal phase of the host material as it is known to have 10 times more photoluminescence efficiency than its cubic counterpart. However the study correlates the synthesized thin film with three annealed films (400°C , 500°C , 600°C) for proper analysis of X-ray diffraction, TEM, absorption, PL and its calorimetric shifts etc. Interestingly, with a change in annealing temperature, a calorimetric shift is observed in upconverted emission from green (539 nm) to yellow (655 nm), to red (675 nm). The complete phase transformation from hexagonal to cubic is also seen with morphological changes and commensurate rise in photoluminescence efficiency.

Deposition Methods for Thin Films: The research then shifts to the development of deposition techniques for upconversion materials, leading to the formation of blended thin films that can be integrated with photodetectors.

Measurement and Analysis of Retrofits: In this study, we have presented our findings on the advancement of a process and signal optimized polymer-inorganic hybrid upconversion thin film on glass (UTFG) technology. The objective of this technology is to enhance near-infrared (NIR) detection by utilizing a conventional silicon-based detector. The upconversion nanoparticles (UCNPs) films are tested by stacking the film on commercial Newport (918D-UV-OD3) detector. When compared to a control device made with dielectrically equivalent but upconversion-inert silica nanoparticles, the UCNP device shows a 9.12 % increase in photocurrent. Our measurements of photocurrent showed a 21.16 % increase using a low-cost commercial silicon detector that cost less than five dollars. The materials were tested with a single excitation source, 980 nm in near-infrared, but given the usage of a low-cost detector and a simple glass filter, this platform can be further expanded with adjustments in UCNP chemistry for different wavelengths in the NIR range.

Alongside, silicon-based pin diodes are fabricated using a simplified process with UCNP thin films. We have developed an upconversion detector in which the thin film of a blend of an upconversion material/ polymer on glass is combined with the fabricated silicon-based pin diodes to enhance NIR detection. The marginal cost of upconversion-based silicon detectors in this study is around $\sim$ USD 7 compared to existing infrared detectors costing USD 25. The responsivity of the fabricated pin diodes

is found to be maximum at ~ 980 nm wavelength using multiple light sources starting from ultraviolet emitting LED to near infrared source.

In summary, this dissertation covers the synthesis of upconversion nanoparticles (UCNPs), their characterization, film formation on glass, retrofitting the UCNP layer onto two commercial devices, and the fabrication of pin diodes, along with the optical and electrical results.

सार

अपकन्वर्जन सामग्रियों का उपयोग करने वाले निकट-अवरक्त (NIR) डिटेक्टर इमेजिंग, सेंसिंग और संचार सहित विभिन्न अनुप्रयोगों के लिए एक आशाजनक तकनीक है। अपकन्वर्जन सामग्रियों का उपयोग आम तौर पर लंबी-तरंग दैर्ध्य वाले NIR फोटॉनों को छोटी-तरंग दैर्ध्य वाले दृश्यमान या पराबैंगनी फोटॉनों में बदलने के लिए किया जाता है, जिन्हें सिलिकॉन-आधारित फोटोडायोड जैसे पारंपरिक फोटोडिटेक्टरों का उपयोग करके आसानी से पहचाना जा सकता है। यह अपकन्वर्जन प्रक्रिया NIR प्रकाश का कुशल पता लगाने की अनुमति देती है, जिसे पारंपरिक डिटेक्टरों से सीधे पता लगाना अन्यथा चुनौतीपूर्ण होता है। इस प्रक्रिया में लैंथेनाइड-डोपड क्रिस्टल या नैनोकण शामिल होते हैं जो कई कम-ऊर्जा वाले NIR फोटॉनों को अवशोषित कर सकते हैं और अपनी ऊर्जा को मिलाकर दृश्यमान या पराबैंगनी रेंज में एक उच्च-ऊर्जा वाला फोटॉन उत्सर्जित कर सकते हैं। इस प्रक्रिया को अक्सर एंटी-स्टोक्स या अपकन्वर्जन ल्यूमिनेसेंस कहा जाता है। जब NIR प्रकाश (आमतौर पर 700 एनएम से 1700 एनएम की सीमा में) अपकन्वर्जन सामग्री पर पड़ता है, तो इसे लैंथेनाइड डोपेंट द्वारा अवशोषित कर लिया जाता है। कई अवशोषित NIR फोटॉनों से ऊर्जा को एक इलेक्ट्रॉन को उच्च ऊर्जा स्तर पर बढ़ावा देने के लिए संयोजित किया जाता है। उत्तेजित इलेक्ट्रॉन अंततः दृश्यमान या पराबैंगनी रेंज में उच्च-ऊर्जा फोटॉन उत्सर्जित करके अपनी मूल अवस्था में आराम करता है। उत्सर्जित फोटॉन को फिर एक पारंपरिक फोटोडिटेक्टर का उपयोग करके पता लगाया जाता है।

अपकन्वर्जन सामग्री संश्लेषण और विश्लेषण: यह शोध प्रबंध अपकन्वर्जन सामग्री, $\text{NaYF}_4:\text{Yb, Er, Gd}$ के संश्लेषण पर केंद्रित है, जो Si-आधारित डिटेक्टरों पर इसकी पतली परत को फिर से जोड़ने के लिए थर्मल अपघटन विधि के माध्यम से है। अध्ययन संभावित डिटेक्टरों के लिए इस महत्वपूर्ण फोटोनिक सामग्री के लिए इष्टतम एनीलिंग स्थितियों को स्थापित करता है। सामग्री को मेजबान सामग्री के लगभग शुद्ध हेक्सागोनल चरण को प्राप्त करने के लिए 320 C पर संश्लेषित किया जाता है क्योंकि यह अपने क्यूबिक समकक्ष की तुलना में 10 गुना अधिक फोटोल्यूमिनेसेंस दक्षता के लिए जाना जाता है। हालांकि अध्ययन ने एक्स-रे विवर्तन, टीईएम, अवशोषण, पीएल और इसके कैलोरीमेट्रिक शिफ्ट आदि के उचित विश्लेषण के लिए संश्लेषित पतली फिल्म को तीन एनीलिंग फिल्मों (400 डिग्री सेल्सियस, 500 डिग्री सेल्सियस, 600 डिग्री सेल्सियस) के साथ सहसंबंधित किया है। दिलचस्प बात यह है कि एनीलिंग तापमान में बदलाव के साथ, हरे (539 एनएम) से पीले (655 एनएम), लाल (675 एनएम) तक अपकन्वर्टेड उत्सर्जन में कैलोरीमेट्रिक शिफ्ट देखी जाती है। हेक्सागोनल से क्यूबिक में पूर्ण चरण परिवर्तन भी रूपात्मक परिवर्तनों और फोटोल्यूमिनेसेंस दक्षता में समान वृद्धि के साथ देखा जाता है।

पतली फिल्मों के लिए जमाव विधियाँ: फिर अनुसंधान अपकन्वर्जन सामग्री के लिए जमाव तकनीकों के विकास की ओर बढ़ता है, जिससे मिश्रित पतली फिल्मों का निर्माण होता है जिन्हें फोटोडिटेक्टर के साथ एकीकृत किया जा सकता है।

रेट्रोफिट का मापन और विश्लेषण: इस अध्ययन में, हमने प्रक्रिया और संकेत अनुकूलित पॉलिमर-अकार्बनिक हाइब्रिड अपकन्वर्जन थिन फिल्म ऑन ग्लास (UTFG) तकनीक की उन्नति पर अपने निष्कर्ष प्रस्तुत किए हैं। इस तकनीक का उद्देश्य पारंपरिक सिलिकॉन-आधारित डिटेक्टर का उपयोग करके निकट-अवरक्त (NIR) पहचान को बढ़ाना है। अपकन्वर्जन नैनोपार्टिकल्स (UCNPs) फिल्मों का परीक्षण कमर्शियल न्यूपोर्ट (918D-UV-OD3) डिटेक्टर पर फिल्म को स्टैक करके किया जाता है। जब डाइइलेक्ट्रिकली समतुल्य लेकिन अपकन्वर्जन-निष्क्रिय सिलिका नैनोपार्टिकल्स से बने कंट्रोल डिवाइस से तुलना की जाती है, तो UCNP डिवाइस फोटोकंट में 9.12 % की वृद्धि दिखाती है। फोटोकंट के हमारे माप ने कम लागत वाले कमर्शियल सिलिकॉन डिटेक्टर का उपयोग करके 21.16 % की वृद्धि दिखाई, जिसकी कीमत पाँच डॉलर से कम थी। सामग्रियों का परीक्षण एक एकल उत्तेजना स्रोत, निकट-अवरक्त में 980 एनएम के साथ किया गया था, लेकिन कम लागत वाले डिटेक्टर और एक साधारण ग्लास फ़िल्टर के उपयोग को देखते हुए, इस प्लेटफ़ॉर्म को NIR रेंज में विभिन्न तरंग दैर्ध्य के लिए UCNP रसायन विज्ञान में समायोजन के साथ आगे बढ़ाया जा सकता है।

साथ ही, सिलिकॉन-आधारित पिन डायोड को UCNP पतली फिल्मों के साथ एक सरलीकृत प्रक्रिया का उपयोग करके तैयार किया जाता है। हमने एक अपकन्वर्जन डिटेक्टर विकसित किया है जिसमें ग्लास पर अप-

कन्वर्जन सामग्री/पॉलिमर के मिश्रण की पतली फिल्म को NIR डिटेक्शन को बढ़ाने के लिए निर्मित सिलिकॉन-आधारित पिन डायोड के साथ जोड़ा जाता है। इस अध्ययन में अपकन्वर्जन-आधारित सिलिकॉन डिटेक्टरों की सीमांत लागत मौजूदा अवरक्त डिटेक्टरों की लागत 25 अमेरिकी डॉलर की तुलना में लगभग $\sim$ USD 7 है। निर्मित पिन डायोड की प्रतिक्रियाशीलता पराबैंगनी उत्सर्जक एलईडी से लेकर निकट अवरक्त स्रोत तक कई प्रकाश स्रोतों का उपयोग करके $\sim$ 980 एनएम तरंग दैर्ध्य पर अधिकतम पाई गई है।

ਸਾਰ

ਅੱਪਕਨਵਰਜ਼ਨ ਸਮੱਗਰੀ ਦੀ ਵਰਤੋਂ ਕਰਨ ਵਾਲੇ ਨਿਅਰ-ਇਨਫਰਾਰੈੱਡ (NIR) ਡਿਟੈਕਟਰ ਇਮੇਜਿੰਗ, ਸੈਂਸਿੰਗ ਅਤੇ ਸੰਚਾਰ ਸਮੇਤ ਵੱਖ-ਵੱਖ ਐਪਲੀਕੇਸ਼ਨਾਂ ਲਈ ਇੱਕ ਵਾਅਦਾ ਕਰਨ ਵਾਲੀ ਤਕਨਾਲੋਜੀ ਹਨ। ਅੱਪਕਨਵਰਜ਼ਨ ਸਮੱਗਰੀ ਆਮ ਤੌਰ 'ਤੇ ਲੰਬੀ-ਵੇਵਲ-ਲੰਬਾਈ ਵਾਲੇ NIR ਫੋਟੋਨਾਂ ਨੂੰ ਛੋਟੀ-ਵੇਵਲ-ਲੰਬਾਈ ਵਾਲੇ ਦ੍ਰਿਸ਼ਮਾਨ ਜਾਂ ਅਲਟਰਾਵਾਇਲਟ ਫੋਟੋਨਾਂ ਵਿੱਚ ਬਦਲਣ ਲਈ ਵਰਤੀ ਜਾਂਦੀ ਹੈ, ਜਿਸਨੂੰ ਸਿਲੀਕਾਨ-ਅਧਾਰਿਤ ਫੋਟੋਡਾਇਓਡ ਵਰਗੇ ਰਵਾਇਤੀ ਫੋਟੋਡਿਟੈਕਟਰਾਂ ਦੀ ਵਰਤੋਂ ਕਰਕੇ ਆਸਾਨੀ ਨਾਲ ਖੋਜਿਆ ਜਾ ਸਕਦਾ ਹੈ। ਇਹ ਅੱਪਕਨਵਰਜ਼ਨ ਪ੍ਰਕਿਰਿਆ NIR ਰੇਸ਼ਨੀ ਦੀ ਕੁਸ਼ਲ ਖੋਜ ਦੀ ਆਗਿਆ ਦਿੰਦੀ ਹੈ, ਜਿਸਦਾ ਸਿੱਧਾ ਪਤਾ ਲਗਾਉਣਾ ਰਵਾਇਤੀ ਡਿਟੈਕਟਰਾਂ ਨਾਲ ਚੁਣੌਤੀਪੂਰਨ ਹੁੰਦਾ ਹੈ। ਇਸ ਪ੍ਰਕਿਰਿਆ ਵਿੱਚ ਲੈਂਥਾਨਾਈਡ-ਡੋਪਡ ਕ੍ਰਿਸਟਲ ਜਾਂ ਨੈਨੋਪਾਰਟਿਕਲ ਸ਼ਾਮਲ ਹੁੰਦੇ ਹਨ ਜੋ ਕਈ ਘੱਟ-ਊਰਜਾ ਵਾਲੇ NIR ਫੋਟੋਨਾਂ ਨੂੰ ਸੋਖ ਸਕਦੇ ਹਨ ਅਤੇ ਦ੍ਰਿਸ਼ਮਾਨ ਜਾਂ ਅਲਟਰਾਵਾਇਲਟ ਰੇਂਜ ਵਿੱਚ ਇੱਕ ਸਿੰਗਲ ਉੱਚ-ਊਰਜਾ ਵਾਲੇ ਫੋਟੋਨ ਨੂੰ ਛੱਡਣ ਲਈ ਆਪਣੀ ਊਰਜਾ ਨੂੰ ਜੋੜ ਸਕਦੇ ਹਨ। ਇਸ ਪ੍ਰਕਿਰਿਆ ਨੂੰ ਅਕਸਰ ਐਂਟੀ-ਸਟੋਕਸ ਜਾਂ ਅੱਪਕਨਵਰਜ਼ਨ ਲੂਮੀਨੈਂਸ ਕਿਹਾ ਜਾਂਦਾ ਹੈ। ਜਦੋਂ NIR ਰੇਸ਼ਨੀ (ਆਮ ਤੌਰ 'ਤੇ 700 nm ਤੋਂ 1700 nm ਦੀ ਰੇਂਜ ਵਿੱਚ) ਅੱਪਕਨਵਰਜ਼ਨ ਸਮੱਗਰੀ 'ਤੇ ਵਾਪਰਦੀ ਹੈ, ਤਾਂ ਇਹ ਲੈਂਥਾਨਾਈਡ ਡੋਪੈਂਟਾਂ ਦੁਆਰਾ ਸੋਖ ਲਈ ਜਾਂਦੀ ਹੈ। ਕਈ ਸੋਖੇ ਗਏ NIR ਫੋਟੋਨਾਂ ਤੋਂ ਪ੍ਰਾਪਤ ਊਰਜਾ ਨੂੰ ਇੱਕ ਇਲੈਕਟ੍ਰੌਨ ਨੂੰ ਉੱਚ ਊਰਜਾ ਪੱਧਰ 'ਤੇ ਉਤਸ਼ਾਹਿਤ ਕਰਨ ਲਈ ਜੋੜਿਆ ਜਾਂਦਾ ਹੈ। ਉਤਸ਼ਾਹਿਤ ਇਲੈਕਟ੍ਰੌਨ ਅੰਤ ਵਿੱਚ ਦ੍ਰਿਸ਼ਮਾਨ ਜਾਂ ਅਲਟਰਾਵਾਇਲਟ ਰੇਂਜ ਵਿੱਚ ਇੱਕ ਉੱਚ-ਊਰਜਾ ਵਾਲੇ ਫੋਟੋਨ ਨੂੰ ਛੱਡ ਕੇ ਆਪਣੀ ਜ਼ਮੀਨੀ ਅਵਸਥਾ ਵਿੱਚ ਆਰਾਮ ਕਰਦਾ ਹੈ। ਫਿਰ ਇੱਕ ਰਵਾਇਤੀ ਫੋਟੋਡਿਟੈਕਟਰ ਦੀ ਵਰਤੋਂ ਕਰਕੇ ਉਤਸਰਜਿਤ ਫੋਟੋਨ ਦਾ ਪਤਾ ਲਗਾਇਆ ਜਾਂਦਾ ਹੈ।

ਇਹ ਖੋਜ-ਪ੍ਰਬੰਧ Si-ਅਧਾਰਿਤ ਡਿਟੈਕਟਰਾਂ 'ਤੇ ਇਸਦੀ ਪਤਲੀ ਪਰਤ ਨੂੰ ਰੀਟ੍ਰੇਫਿਟ ਕਰਨ ਲਈ ਥਰਮਲ ਸੜਨ ਵਿਧੀ ਰਾਹੀਂ ਅਪਕਨਵਰਜ਼ਨ ਸਮੱਗਰੀ, $\text{NaYF}_4:\text{Yb}$, Er, Gd ਦੇ ਸੰਸਲੇਸ਼ਣ 'ਤੇ ਕੇਂਦਰਿਤ ਕਰਦਾ ਹੈ। ਅਧਿਐਨ ਸੰਭਾਵੀ ਡਿਟੈਕਟਰਾਂ ਲਈ ਇਸ ਮਹੱਤਵਪੂਰਨ ਫੋਟੋਨਿਕ ਸਮੱਗਰੀ ਲਈ ਅਨੁਕੂਲ ਐਨੀਲਿੰਗ ਸਥਿਤੀਆਂ ਸਥਾਪਤ ਕਰਦਾ ਹੈ। ਹੋਸਟ ਸਮੱਗਰੀ ਦੇ ਲਗਭਗ ਸ਼ੁੱਧ ਹੈਕਸਾਗੋਨਲ ਪੜਾਅ ਨੂੰ ਪ੍ਰਾਪਤ ਕਰਨ ਲਈ ਸਮੱਗਰੀ ਨੂੰ 320 ਡਿਗਰੀ ਸੈਲਸੀਅਸ 'ਤੇ ਸੰਸਲੇਸ਼ਿਤ ਕੀਤਾ ਜਾਂਦਾ ਹੈ ਕਿਉਂਕਿ ਇਸਨੂੰ ਇਸਦੇ ਘਣ ਹਮਰੁਤਬਾ ਨਾਲੋਂ 10 ਗੁਣਾ ਜ਼ਿਆਦਾ ਫੋਟੋਲੂਮਿਨੈਂਸ ਕੁਸ਼ਲਤਾ ਲਈ ਜਾਣਿਆ ਜਾਂਦਾ ਹੈ। ਹਾਲਾਂਕਿ, ਅਧਿਐਨ ਐਕਸ-ਰੇ ਵਿਭਿੰਨਤਾ, TEM, ਸੋਖਣ, PL ਅਤੇ ਇਸਦੇ ਕੈਲੋਰੀਮੈਟ੍ਰਿਕ ਸ਼ਿਫਟਾਂ ਆਦਿ ਦੇ ਸਹੀ ਵਿਸ਼ਲੇਸ਼ਣ ਲਈ ਤਿੰਨ ਐਨੀਲਡ ਫਿਲਮਾਂ (400 ਡਿਗਰੀ ਸੈਲਸੀਅਸ, 500 ਡਿਗਰੀ ਸੈਲਸੀਅਸ, 600 ਡਿਗਰੀ ਸੈਲਸੀਅਸ) ਨਾਲ ਸਿੰਥੇਸਾਈਜ਼ਡ ਪਤਲੀ ਫਿਲਮ ਨੂੰ ਕੋਰਲੇਟ ਕਰਦਾ ਹੈ। ਦਿਲਚਸਪ ਗੱਲ ਇਹ ਹੈ ਕਿ ਐਨੀਲਿੰਗ ਤਾਪਮਾਨ ਵਿੱਚ ਤਬਦੀਲੀ ਦੇ ਨਾਲ, ਹਰੇ (539 nm) ਤੋਂ ਪੀਲੇ (655 nm), ਲਾਲ (675 nm) ਵਿੱਚ ਅਪਕਨਵਰਟਡ ਨਿਕਾਸ ਵਿੱਚ ਇੱਕ ਕੈਲੋਰੀਮੈਟ੍ਰਿਕ ਸ਼ਿਫਟ ਦੇਖਿਆ ਜਾਂਦਾ ਹੈ। ਹੈਕਸਾਗੋਨਲ ਤੋਂ ਕਿਊਬਿਕ ਵਿੱਚ ਪੂਰਾ ਪੜਾਅ ਪਰਿਵਰਤਨ ਰੂਪ ਵਿਗਿਆਨਿਕ ਤਬਦੀਲੀਆਂ ਅਤੇ ਫੋਟੋਲੂਮਿਨੈਂਸ ਕੁਸ਼ਲਤਾ ਵਿੱਚ ਅਨੁਪਾਤਕ ਵਾਧੇ ਦੇ ਨਾਲ ਵੀ ਦੇਖਿਆ ਜਾਂਦਾ ਹੈ।

ਪਤਲੀਆਂ ਫਿਲਮਾਂ ਲਈ ਜਮ੍ਹਾਂ ਕਰਨ ਦੇ ਤਰੀਕੇ: ਖੋਜ ਫਿਰ ਅਪਕਨਵਰਜ਼ਨ ਸਮੱਗਰੀ ਲਈ ਜਮ੍ਹਾਂ ਕਰਨ ਦੀਆਂ ਤਕਨੀਕਾਂ ਦੇ ਵਿਕਾਸ ਵੱਲ ਬਦਲਦੀ ਹੈ, ਜਿਸ ਨਾਲ ਮਿਸ਼ਰਤ ਪਤਲੀਆਂ ਫਿਲਮਾਂ ਦਾ ਗਠਨ ਹੁੰਦਾ ਹੈ ਜਿਨ੍ਹਾਂ ਨੂੰ ਫੋਟੋਡਿਟੈਕਟਰਾਂ ਨਾਲ ਜੋੜਿਆ ਜਾ ਸਕਦਾ ਹੈ।

ਰੀਟਰੇਫਿਟਸ ਦਾ ਮਾਪ ਅਤੇ ਵਿਸ਼ਲੇਸ਼ਣ: ਇਸ ਅਧਿਐਨ ਵਿੱਚ, ਅਸੀਂ ਇੱਕ ਪ੍ਰਕਿਰਿਆ ਅਤੇ ਸਿਗਨਲ ਅਨੁਕੂਲਿਤ ਪੋਲੀਮਰ-ਇਨਆਰਗੈਨਿਕ ਹਾਈਬ੍ਰਿਡ ਅਪਕਨਵਰਜ਼ਨ ਥਿਨ ਫਿਲਮ ਆਨ ਗਲਾਸ (UTFG) ਤਕਨਾਲੋਜੀ ਦੀ ਤਰੱਕੀ 'ਤੇ ਆਪਣੇ ਨਤੀਜੇ ਪੇਸ਼ ਕੀਤੇ ਹਨ। ਇਸ ਤਕਨਾਲੋਜੀ ਦਾ ਉਦੇਸ਼ ਇੱਕ ਰਵਾਇਤੀ ਸਿਲੀਕਾਨ-ਅਧਾਰਿਤ ਡਿਟੈਕਟਰ ਦੀ ਵਰਤੋਂ ਕਰਕੇ ਨੇੜੇ-ਇਨਫਰਾਰੈੱਡ (NIR) ਖੋਜ ਨੂੰ ਵਧਾਉਣਾ ਹੈ। ਅਪਕਨਵਰਜ਼ਨ ਨੈਨੋਪਾਰਟਿਕਲ (UCNPs) ਫਿਲਮਾਂ ਦੀ ਜਾਂਚ ਫਿਲਮ ਨੂੰ ਵਪਾਰਕ ਨਿਊਪੋਰਟ (918D-UV-OD3) ਡਿਟੈਕਟਰ 'ਤੇ ਸਟੈਕ ਕਰਕੇ ਕੀਤੀ ਜਾਂਦੀ ਹੈ। ਜਦੋਂ ਡਾਇਲੈਕਟ੍ਰਿਕ ਤੌਰ 'ਤੇ ਬਰਾਬਰ ਪਰ ਅਪਕਨਵਰਜ਼ਨ-ਇਨਰਟ ਸਿਲਿਕਾ ਨੈਨੋਪਾਰਟਿਕਲ ਨਾਲ ਬਣੇ ਕੰਟਰੋਲ ਡਿਵਾਈਸ ਨਾਲ ਤੁਲਨਾ ਕੀਤੀ ਜਾਂਦੀ ਹੈ, ਤਾਂ UCNP ਡਿਵਾਈਸ ਫੋਟੋਕਰੰਟ ਵਿੱਚ 9.12% ਵਾਧਾ ਦਿਖਾਉਂਦੀ ਹੈ। ਫੋਟੋਕਰੰਟ ਦੇ ਸਾਡੇ ਮਾਪਾਂ ਨੇ ਘੱਟ-ਲਾਗਤ ਵਾਲੇ ਵਪਾਰਕ ਸਿਲੀਕਾਨ ਡਿਟੈਕਟਰ ਦੀ ਵਰਤੋਂ ਕਰਕੇ 21.16% ਵਾਧਾ ਦਿਖਾਇਆ ਜਿਸਦੀ ਕੀਮਤ ਪੰਜ ਡਾਲਰ ਤੋਂ ਘੱਟ ਹੈ। ਸਮੱਗਰੀ ਦੀ ਜਾਂਚ ਇੱਕ ਸਿੰਗਲ ਐਕਸਾਈਟੇਸ਼ਨ ਸਰੋਤ, ਨੇੜੇ-ਇਨਫਰਾਰੈੱਡ ਵਿੱਚ 980 nm ਨਾਲ ਕੀਤੀ ਗਈ ਸੀ, ਪਰ ਇੱਕ ਘੱਟ-ਲਾਗਤ ਵਾਲੇ ਡਿਟੈਕਟਰ ਅਤੇ ਇੱਕ ਸਧਾਰਨ ਸੀਸ਼ੇ ਦੇ ਫਿਲਟਰ ਦੀ ਵਰਤੋਂ ਨੂੰ ਦੇਖਦੇ ਹੋਏ, ਇਸ ਪਲੇਟਫਾਰਮ ਨੂੰ NIR ਰੇਂਜ ਵਿੱਚ ਵੱਖ-ਵੱਖ ਤਰੰਗ-ਲੰਬਾਈ ਲਈ UCNP ਰਸਾਇਣ ਵਿਗਿਆਨ ਵਿੱਚ ਸਮਾਯੋਜਨ ਨਾਲ ਹੋਰ ਵਧਾਇਆ

ਜਾ ਸਕਦਾ ਹੈ।

ਇਸ ਦੇ ਨਾਲ, ਸਿਲੀਕਾਨ-ਅਧਾਰਿਤ ਪਿੰਨ ਡੀਡੇਜ਼ ਨੂੰ UCNP ਪਤਲੀਆਂ ਫਿਲਮਾਂ ਨਾਲ ਇੱਕ ਸਰਲ ਪ੍ਰਕਿਰਿਆ ਦੀ ਵਰਤੋਂ ਕਰਕੇ ਬਣਾਇਆ ਜਾਂਦਾ ਹੈ। ਅਸੀਂ ਇੱਕ ਅਪਕਨਵਰਜ਼ਨ ਡਿਟੈਕਟਰ ਵਿਕਸਤ ਕੀਤਾ ਹੈ ਜਿਸ ਵਿੱਚ ਸ਼ੀਸ਼ੇ 'ਤੇ ਇੱਕ ਅਪਕਨਵਰਜ਼ਨ ਸਮੱਗਰੀ/ਪੋਲੀਮਰ ਦੇ ਮਿਸ਼ਰਣ ਦੀ ਪਤਲੀ ਫਿਲਮ ਨੂੰ NIR ਖੋਜ ਨੂੰ ਵਧਾਉਣ ਲਈ ਫੈਬਰੀਕੇਟਿਡ ਸਿਲੀਕਾਨ-ਅਧਾਰਿਤ ਪਿੰਨ ਡਾਇਓਡਸ ਨਾਲ ਜੋੜਿਆ ਜਾਂਦਾ ਹੈ। ਇਸ ਅਧਿਐਨ ਵਿੱਚ ਅਪਕਨਵਰਜ਼ਨ-ਅਧਾਰਿਤ ਸਿਲੀਕਾਨ ਡਿਟੈਕਟਰਾਂ ਦੀ ਸੀਮਾਂਤ ਲਾਗਤ ਮੌਜੂਦਾ ਇਨਫਰਾਰੈੱਡ ਡਿਟੈਕਟਰਾਂ ਦੇ ਮੁਕਾਬਲੇ ਲਗਭਗ $\sim$ USD 7 ਹੈ ਜਿਨ੍ਹਾਂ ਦੀ ਕੀਮਤ USD 25 ਹੈ। ਫੈਬਰੀਕੇਟਿਡ ਪਿੰਨ ਡਾਇਓਡਸ ਦੀ ਜ਼ਿੰਮੇਵਾਰੀ ਅਲਟਰਾਵਾਇਲਟ ਐਮੀਟਿੰਗ LED ਤੋਂ ਲੈ ਕੇ ਨੇੜੇ ਇਨਫਰਾਰੈੱਡ ਸਰੋਤ ਤੱਕ ਕਈ ਪ੍ਰਕਾਸ਼ ਸਰੋਤਾਂ ਦੀ ਵਰਤੋਂ ਕਰਦੇ ਹੋਏ $\sim$ 980 nm ਤਰੰਗ-ਲੰਬਾਈ 'ਤੇ ਵੱਧ ਤੋਂ ਵੱਧ ਪਾਈ ਗਈ ਹੈ।

ਸੰਖੇਪ ਵਿੱਚ, ਇਹ ਖੋਜ ਨਿਬੰਧ ਅੱਪਕਨਵਰਜ਼ਨ ਨੈਨੋਪਾਰਟਿਕਲ (UCNPs) ਦੇ ਸੰਸਲੇਸ਼ਣ, ਉਨ੍ਹਾਂ ਦੀ ਵਿਸ਼ੇਸ਼ਤਾ, ਸ਼ੀਸ਼ੇ 'ਤੇ ਫਿਲਮ ਨਿਰਮਾਣ, UCNP ਪਰਤ ਨੂੰ ਦੋ ਵਪਾਰਕ ਡਿਵਾਈਸਾਂ 'ਤੇ ਰੀਟਰੋਫਿਟਿੰਗ, ਅਤੇ ਆਪਟੀਕਲ ਅਤੇ ਇਲੈਕਟ੍ਰੀਕਲ ਨਤੀਜਿਆਂ ਦੇ ਨਾਲ ਪਿੰਨ ਡਾਇਓਡਸ ਦੇ ਨਿਰਮਾਣ ਨੂੰ ਕਵਰ ਕਰਦਾ ਹੈ।

Contents

Certificate	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	v
LIST OF FIGURES	xvii
LIST OF TABLES	1
1 Introduction	1
1.1 Introduction	1
1.2 Types of NIR Detectors	1
1.3 Performance Metrics	2
1.4 IR Detector Market	4
1.5 Advantages	6
1.6 Limitations	6
1.7 State of the art photodetectors	6
1.8 Upconversion Materials and its photophysics	9
1.9 Thesis Organization	13
2 Methods and Material Characterization	15
2.1 Existing methods of synthesis	15
2.2 Synthesis of NaYF ₄ for Upconversion	16
2.3 Film Formation process	17
2.4 Elemental Characterization	17
2.5 Design for PL Setup	19
2.5.1 Free space experiment	19
2.5.2 Final Assembly	20
2.6 Commercial diode selection	20
2.7 Simulation of p-n junction device	21
3 Optimizing structural properties of cubic NaYF₄ nanomaterials	25
3.1 Introduction	25
3.2 Experimental Section	26
3.3 Results and discussions	26

3.3.1	Annealed Results	26
3.3.2	Photoluminescence (PL) Response	27
3.4	Conclusion	29
4	Photonic upconversion in solution-processed Gd-based thin films	31
4.1	Introduction	31
4.2	Experimental Details	31
4.2.1	Synthesis / Film formation	31
4.3	Results and Discussion	32
4.4	Conclusion	36
5	Effect of annealing temperature on colorimetric shifts and upconversion photoluminescence in Gd-doped NaYF₄ thin films	37
5.1	Introduction	37
5.2	Methods	37
5.2.1	Synthesis of upconversion material	37
5.3	Results and Discussion	38
5.3.1	Loading effect on Photoluminescence (PL)	38
5.3.2	X-ray diffraction analysis for thin films	39
5.3.3	Transmission and Absorption analysis	39
5.3.4	Photo-luminescence (PL) analysis	40
5.3.5	CIE data	41
5.4	Conclusions	41
6	Upconversion in Gd-doped nanocomposite thin-films for retrofitted Si-based near-infrared detectors	45
6.1	Introduction	45
6.2	Experimental Section	46
6.2.1	Synthesis of upconversion material	46
6.2.2	Characterization	46
6.2.3	Optical Set-up	46
6.3	Results and Discussion	48
6.3.1	Ellipsometry measurements	50
6.4	Conclusions	60
7	Upconversion-film enhanced pin-diode based photodetectors	61
7.1	Introduction	61
7.2	Methods	62
7.2.1	pin detector fabrication	62
7.2.2	Synthesis of upconversion material	62
7.2.3	Characterization	64
7.2.4	Optical Set-up	64
7.3	Results and Discussion	64
7.4	Conclusion	67

8	Conclusions and Future Work	71
	Additional work	72
A	New Upconversion Materials	75
A.1	Fluoride based upconversion materials	75
A.2	Perovskite materials in upconversion	75
B	p-n diode fabrication	79
C	Code	81
D	Publications	87
D.1	Journal/Conference articles	87
D.1.1	Under revision/review	87
D.1.2	Published	87
D.2	Patents	88
D.3	Conference / Workshop presentations	88
E	Biography	89

List of Figures

1.1	Market division for global infrared detector, after a graphic from report <i>Infrared Detector Market by End Use Industry Type, Wavelength & Region</i> (academic fair use, formal copyright permission sought) [32].	4
1.2	Global infrared detector market (\$M) by Application (2016-2021), reproduced from report by Grand View Research Inc. (academic fair use, formal copyright permission sought)[17].	5
1.3	Schematic diagram for infrared detection, reproduced from report <i>Ultrasolic vs Infrared (IR Sensors) - Which Is Better?</i> (academic fair use, formal copyright permission sought) [36].	5
1.4	A) p-i-n waveguide photodiode proposed by Kato et al. [70]. B) The infrared wave collector structure fabricated by AlShareef et al. [71] a) top b) side view. C) A scanning electron micrograph (a) and spectral responsivity (b) of silicon microstructures at two bias levels proposed by Carey et al. [72]. D) SEM image of a Ni-Ge Schottky barrier photodetector designed by Ang et al. [73]. E) Schottky barrier IR photodetector (Cu/p-Si), proposed by Casalino et al. [65]. F) Schottky barrier IR photodetector (Silicide based), proposed by Zhu et al. [66]. G) Schematic of telecom detector, proposed by Tanabe et al. [68] H) Ge-on-SOI photodetector structure [55] I) Graph of quantum efficiency versus Ge thickness at different wavelengths (λ) = 850, 1300, 1550 nm [55]. Figure with reprint permission from: a) ©1991 IEEE b) ©2021 IEEE c) ©2004 IEEE d) ©2008 IEEE e) ©2010 AIP Publishing f) ©2008 AIP Publishing g) ©2010 AIP Publishing h) ©2006 IEEE i) ©2006 IEEE	8
1.5	Schematic diagram for infrared sensor [78]. Reproduced under terms of 37 CFR 1.71(d) & (e) and 1.84(s) (US Federal Code), being not subject to copyright restrictions as a part of a patent application available in public domain.	9
1.6	Schematic diagram for upconversion nanoparticle, reproduced with permission from Elsevier[80].	10
1.7	Effect of temperature on emission intensity of upconversion material. Reproduced from Ref. [94] with permission from the Royal Society of Chemistry.	12
2.1	Synthesis procedure for upconversion nanoparticles using thermal decomposition [83].	18
2.2	Process steps for making UCNP film on glass from solution containing upconversion nanoparticles (UCNPs) with polystyrene polymer and DME as solvent.	18

2.3	(Left) Set-up arranged to compute the angle at which maximum light can be extracted from the sample without hindering the path of the laser source. (Right) Power versus angle measurement for the sample shown. This experiment was done in MTech Optics Lab, Physics Department.	19
2.4	(a) Part assembly diagram from AutoCAD© (b) Final assembly of the whole set-up arranged with the spectrometer interfaced with the laptop (c) Photoluminescence measurement with Nile red ethanol solution excited with 405 nm laser source	20
2.5	(a) The laboratory setup consists of a laser diode, a focusing lens, and an upconverted film placed on top of a glass substrate. The sample is being illuminated by light, which is then directed onto multiple photodiodes in order to identify the most efficient diode for optical studies. The photodiodes are affixed to a 3D printed setup that is designed using AutoCAD©. (b) Updated configuration of the 3D printed setup to minimise the separation between the sample and photodiodes.	21
2.6	Illustration of basis functions shown on 1 element with 2 nodes of 1-D pn junction device. The whole device is divided into multiple elements represented with nodes.	22
2.7	Simulation results show the charge distribution, built-in potential, electric field for 1-D pn junction device with zero bias.	23
3.1	a) SEM b) HRTEM image of as-synthesized upconversion nanoparticles.	27
3.2	(Left) a) X-ray diffraction (XRD) for synthesized UCNPs, NaYF ₄ :Er at 320°C for 90 minutes b) XRD for annealed UCNPs at 400°C for 24 hours c) XRD for annealed UCNPs at 450°C for 24 hours d) XRD for annealed UCNPs at 550°C for 10 hours. In all scans, blue (red) lines correspond to JCPDS data for cubic (hexagonal) phase. (Right) Enhanced X-ray diffraction analysis achieved improved signal quality with reduced noise and baseline corrections for clearer peak visualization.	28
3.3	Photo-luminescence graph shows upconversion in visible with excitation at a) 785 nm b) 980 nm.	29
4.1	(a) X-ray diffraction for the upconversion material, NaYF ₄ : Yb (18%), Er (2%), Gd (15%). Here, the red-dashed (blue - dotted) lines indicate the JCPDS data of hexagonal (cubic) phase (b) High Resolution TEM of the synthesized nanoparticles.	32
4.2	Energy level diagram for NaYF ₄ : Yb/Er/Gd system with a) 785 nm b) 980 nm c) 980 nm excitations. Dotted (...), dashed (—) and patterned (-.-) lines indicate the green, red and blue emissions respectively.	33
4.3	Photoluminescence measurements showing the green and red signals under excitation with 785 nm. From this, 7514.78 is the highest photon count.	35
4.4	a) Quality of film made on glass slide b) Atomic force microscopy (AFM) showing height deviations from the base (glass).	35
4.5	Scanning electron microscope (SEM) of the upconversion film made on the glass slide.	36
5.1	Photoluminescence (PL) spectrum of different mass fractions/ loading ratio of upconversion nanoparticles, NaYF ₄ : Gd, Er, Yb with polystyrene polymer (PS).	38

5.2	Thin film XRD data for the upconversion material, sodium yttrium fluoride doped with ytterbium, erbium, and gadolinium at the synthesized temperature (320°C) and at annealed temperatures (400°C, 500°C, and 600°C). Cubic (C) and hexagonal (H) phase peaks are assigned [163] and matched with standard powder XRD data of hexagonal NaYF ₄ (ICDD 16-0334) and cubic NaYF ₄ (ICDD 77-2042).	42
5.3	Transmission electron microscopy (TEM) characterization of nanoparticles synthesized at (a) 320°C, and annealed at (b) 400°C, (c) 500°C and (d) 600°C respectively. . . .	43
5.4	The UV-VIS absorbance spectra of thin films synthesized at (a) 320°C, and annealed at (b) 400°C, (c) 500°C and (d) 600°C respectively in visible and near infrared range (400 nm - 2000 nm) of electromagnetic spectrum.	43
5.5	(a) Upconversion luminescence (UCPL) spectra recorded for the NaYF ₄ : Gd, Er, Yb thin films using 785 nm excitation source, (b) (left axis) Intensity of the signals emitted at the different temperatures (spectral range A: 515 nm to 570 nm, spectral range B: 640 nm to 700 nm; (right axis) the hexagonal content (%) obtained from XRD data (Fig. 5.2) varying with different temperatures, and the black curve signifies the total PL counts i.e the sum of the number of photons associated with A and B signals, (c) Commission Internationale de l'éclairage (CIE) 1931 coordinates of upconverted emissions for NaYF ₄ : Gd, Er, Yb material at synthesized and annealed temperatures under 785 nm excitation. The color wavelengths of emissions are represented along the locus of CIE curve. . . .	44
6.1	(a) Setup for the free-space experiment used to measure the UCNF detector response. $\mathcal{I}_i(\phi_i)$ and $\mathcal{I}_{u,meas}(\phi_{u,d,meas})$ are the intensities and corresponding photon fluxes (photons m ⁻² s ⁻¹) of the excitation source and the emitted measured response respectively. $\mathcal{I}_i(\phi_i)$ and $\mathcal{I}_F(\phi_F)$ are the light intensities incident on the sample and the detector respectively. T_u and T_F are the normalized transmittance values for the UCNF sample and the employed filter FI. (b) Schematic of the sample and detector assembly with the Newport detector. The detector surface (dark gray) is separated from the sample surface by a distance $r' \equiv r + r_0$, where $r' = 17.2$ mm for the Newport detector, and $r' = r = 2$ mm for the low-cost detector. The laser (marked in green) intersects with the UCNF layer (marked in pink) and defines a region "ILF", containing emissive dipoles located on upconversion nanoparticles (latter marked in dark red).	47
6.2	Powder X-ray Diffraction (PXRD) of the NaYF ₄ :Yb(18%), Er(2%), Gd(15%) UCNPs. Two small diffraction peaks can be indexed to the cubic phase. Red (blue) lines indicate hexagonal (cubic) ICDD data.	48
6.3	(a) High-resolution transmission electron microscopy of near spherical particles with uniform size, ~22 nm. (b) The field emission scanning electron microscopy of the NaYF ₄ :Yb(18%), Er(2%), Gd(15%) UCNPs. (c) Energy dispersive X-ray Analysis (EDX) of NaYF ₄ nanocrystals. The element, carbon found in EDX analysis is due to the carbon tape used as adhesive in the measurement.	49
6.4	(Left axis) Photoluminescence spectrum showing broad green emission from UCNPs excited with 980 nm excitation source along with camera pictures. (Right axis) Transmittance spectra of a blank glass slide (red), upconversion nanoparticles (blue), and silica nanoparticles (black) as a control sample dispersed in polystyrene coated on a glass slide.	50
6.5	Ellipsometry measurement along with results obtained for UCNPs as test sample.	51
6.6	Ellipsometry measurement along with results obtained for Si-Nanoparticles as control sample. .	52

6.7	(a) Transmittance curve for the band pass filter (thickness ≈ 2 mm), FI (left axis-blue) and the response curve for the 918UV-OD3 detector (right axis-green). (b) Output photocurrent (I_d) as a function of filtered beam power (mW, 980 nm) obtained for samples U (red) and S (black). Attenuation of beam power is obtained using neutral density filters. (Inset) log-log plot.(c) Responsivity ($\mu\text{A W}^{-1}$) vs P_i for the modified detector, for samples U (red) and S (black). (Inset) Relative enhancement for the U signal with respect to S. A similar measurement for sample G yields $I_{d,G}=67.3(11)$ pA at the highest incident power.	59
6.8	Photocurrent vs voltage (I-V) characteristics of the low-cost photodetector. Excitation: 980 nm laser diode.	60
7.1	The two device geometries available for the fabrication of pin-diode detector.	61
7.2	Schematic process workflow for fabrication of pin-diode detector. Courtesy: Dr. Rajinder Singh Deol.	63
7.3	On a single wafer, 64 devices were diced into four quadrants, and each detector was diced separately from each quadrant.	65
7.4	(a) Pristine current-voltage characteristics of the fabricated pin-diode detector. (b) Pristine current voltage characteristics of another device with the same geometry as (a) over a restricted voltage range.	66
7.5	Free space experimental setup to measure photocurrent from the upconversion-film enhanced detector. For measurements, an assembled working pin-diode detector is shown. The same setup is being used for pin diode detector and detector N-918D-UV-OD3.	67
7.6	(a) (left axis-blue) Transmission curve for the bandpass filter, FI (thickness ≈ 2 mm), and (right axis) measured responsivity (norm.) curve for the pin-diode detector and detector N918D-UV-OD3. (b) Photocurrent, I_d (pA) versus source beam or input power, P_{in} (mW) obtained after the bandpass filter, FI from the UCNF (test) and Si-nanoparticle (control) samples. (c) (left axis) Difference between test and control photocurrents (pA) vs input power (mW), (right axis) percentage increase. Excitation source: 980 nm.	68
7.7	Responsivity for the fabricated pin-diode (PD) based detectors for test and control devices. Here, PD refers to the bare pin-diode detector.	69
A.1	New upconversion materials that are tested along with NaYF_4 material. The figure (left) shows the x-ray diffraction patterns of different upconverted material with transmission electron microscopy (TEM- right) images of the respective materials for size and shape identification. . . .	76
A.2	The photoluminescence study of the lithium-based upconversion materials synthesized to compare with NaYF_4	77
A.3	(left)X-ray diffraction of the as-synthesized CsPbBr_3 perovskite material along with the TEM image (inset). The size is approximately 14 nm. (right) Optical absorbance spectra on the left vertical axis and photoluminescence spectra on right vertical axis is shown with multiple excitation wavelengths.	77
A.4	(top) Left graph shows the normalized spectral responsivity of the commercial solar cell utilized in this study. Right graph shows the optical current generated with respect to the varying voltage at multiple excitation wavelengths. (bottom) Left graph shows the output current generated with varying input power at multiple excitation wavelengths. Input power was varied by applying different neutral density filters in the path of incoming beam. Right graph shows the responsivity spectra of the solar cell with perovskite film on top of it.	78

B.1	(left) A schematic of the fabricated device. (right) Current-voltage characteristics of the control and test devices. These are preliminary data that require additional analysis to figure out the charging and discharging effects involved.	80
-----	--	----

List of Tables

I.I	List of state of art silicon based photodetectors operating in near infrared region. . . .	7
-----	--	---