

PLASMONICS-ENHANCED INORGANIC SOLAR CELLS

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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PLASMONICS-ENHANCED INORGANIC SOLAR CELLS

by

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*To my father, Radheshyam and
my grandfather, Gaurilal*

CERTIFICATE

This is to certify that the thesis entitled “Plasmonics-Enhanced Inorganic Solar Cells” being submitted by **Mr. Uttam Kumar Kumawat** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, is a record of bonafide research work carried out by him. Mr. Uttam Kumar Kumawat has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

In order to fulfill the growing demand for energy, human beings have exceedingly explored and used the conventional sources of non-renewable energies such as oil, natural gases, and coals. These resources are limited in storage and can lead to environmental pollution and a global climate change. These challenges can be overcome by using solar photovoltaic energy, since the solar power that strikes the earth is more than earth's requirements. The main challenges in photovoltaics are either the cost or the insufficient efficiency of the photovoltaic modules. If a thin absorbing layer is employed in solar cells, the cost of the solar cell modules decreases as less material is employed for the development of the solar cells. On the other hand, as the thickness of the semiconductor layer decreases, the absorption in the active layer decreases, which leads to a decrease in the efficiency solar cells. In order to increase the absorption in the thin semiconductor layer, several light trapping techniques have been introduced. The introduction of plasmonic and photonic nanostructures into the solar cells allows for the possibility of reducing the absorbing layer thicknesses, without compromising with the absorption of light. This can enable the development of low cost and high-efficiency solar cells.

In this thesis, we employ the finite difference time domain (FDTD) method to study the photovoltaic behavior of InGaN alloy-based solar cells and microcrystalline silicon solar cells containing plasmonic and photonic nanostructures.

A lower indium content of an InGaN alloy leads to a large energy band gap of the InGaN active layer. This results in the absorption of sunlight only for shorter wavelengths of light, which leads to low-efficiency solar cells. Thus, in order to realize high-efficiency InGaN based solar cells, the indium contents in the InGaN active layer must be increased to reduce the band gap of the active material. The initial part of the thesis describes a numerical study using FDTD

simulations of the indium-rich InGaN thin-film solar cells. The performances of these thin solar cells are enhanced by incorporating a periodic array of 1-dimensional and 2-dimensional plasmonic and photonic nanostructures on the back side and/or on the front side of the solar cells. We show significantly improved performances of these solar cells by employing a dual nanostructure (i.e. a combination of plasmonic and photonic nanostructures) as compared to the solar cells without nanostructures or having only photonic nanostructures or only plasmonic nanostructures. Moreover, we examine the effect of the single and dual nanostructures on the InGaN solar cells for various indium compositions in the active layer and demonstrate that the dual nanostructure becomes more beneficial for the InGaN solar cells having greater indium compositions and becomes less beneficial for the InGaN solar cells having lower indium compositions. Furthermore, we study the performance of the indium-rich InGaN solar cells containing various plasmonic and photonic nanostructures under oblique light incidence.

The later part of the thesis describes a numerical study of the improved performance of the microcrystalline silicon thin-film solar cells by employing a periodic array of plasmonic nanostructures on the back side of the solar cell. We then show these plasmonic nanostructure arrays increase the absorption for the longer wavelength region, where most of the incident light photons remains unharvested due to extremely low absorption coefficients of the microcrystalline silicon material. We demonstrate that the enhancement in the performance of the cells is attributed to the enhanced electromagnetic fields in the active layer due to surface plasmon resonance based scattering and waveguide modes at these longer wavelengths.

सार

ऊर्जा की बढ़ती मांग को पूरा करने के लिए, मानव ने गैर-नवीकरणीय ऊर्जा जैसे तेल, प्राकृतिक गैसों और कोयले के पारंपरिक स्रोतों का अत्यधिक अन्वेषण और उपयोग किया है। ये संसाधन भंडारण में सीमित हैं और इससे पर्यावरण प्रदूषण और वैश्विक जलवायु परिवर्तन हो सकता है। सौर फोटोवोल्टिक ऊर्जा का उपयोग करके इन चुनौतियों को दूर किया जा सकता है, क्योंकि पृथ्वी की सतह पर आने वाली सौर ऊर्जा पृथ्वी की आवश्यकताओं से अधिक है। फोटोवोल्टिक्स में मुख्य चुनौतियां या तो लागत या फोटोवोल्टिक मॉड्यूल की अपर्याप्त दक्षता हैं। यदि सौर सेल में एक पतली अवशोषित परत नियोजित की जाती है, तो सौर सेल के विकास के लिए कम सामग्री के रूप में सौर सेल मॉड्यूल की लागत कम हो जाती है। दूसरी ओर, जैसे-जैसे अर्धचालक परत की मोटाई घटती जाती है, सक्रिय परत में अवशोषण कम होता जाता है, जिससे सौर सेल की दक्षता में कमी होती है। पतली अर्धचालक परत में अवशोषण को बढ़ाने के लिए, कई प्रकाश फँसाने की तकनीक शुरू की गई हैं। सौर सेल में प्लाज्मोनिक और फोटोनिक नैनोसंरचनाओं का उपयोग प्रकाश के अवशोषण के साथ समझौता किए बिना, अवशोषित परत की मोटाई को कम करने की संभावना के लिए अनुमति देता है। यह कम लागत और उच्च दक्षता वाले सौर सेल के विकास को सक्षम कर सकता है।

इस थीसिस में हम फोटोनिक और प्लास्मोनिक नैनोसंरचनाओं युक्त InGaN मिश्र धातु-आधारित सौर सेल और माइक्रोक्रीस्टलाइन सिलिकॉन सौर सेल के फोटोवोल्टिक व्यवहार का अध्ययन करने के लिए **Finite Difference Time Domain (FDTD)** विधि का उपयोग करते हैं।

एक InGaN मिश्र धातु में कम इंडियम की मात्रा के कारण InGaN सक्रिय परत का ऊर्जा बैंड गैप अधिक होता है। जिसके फलस्वरूप सूर्य के प्रकाश की केवल कम तरंग दैर्घ्यों का ही अवशोषण हो पाता है, जो कम दक्षता वाले सौर सेल की ओर जाता है। इस प्रकार, उच्च दक्षता वाले InGaN आधारित सौर सेल के निर्माण के लिए, InGaN सक्रिय परत में इंडियम की मात्रा को सक्रिय पदार्थ के बैंड गैप को कम करने के लिए बढ़ाया जाना चाहिए। थीसिस का प्रारंभिक भाग इंडियम-समृद्ध InGaN पतली-फिल्म सौर सेल के FDTD सिमुलेशन का उपयोग करके एक संख्यात्मक अध्ययन का वर्णन करता है। इन पतले सौर सेल के प्रदर्शन को 1-आयामी और 2-आयामी प्लास्मोनिक और फोटोनिक नैनोसंरचनाओं के सौर सेल के पीछे की ओर या सौर सेल के सामने की तरफ शामिल करके बढ़ाया जाता है। हम नैनोसंरचना के बिना सौर सेल की तुलना में या केवल फोटोनिक नैनोसंरचना या केवल प्लास्मोनिक नैनोसंरचना होने की तुलना में एक दोहरी नैनोसंरचना (यानी प्लास्मोनिक और फोटोनिक नैनोसंरचनाओं के संयोजन) को नियोजित करके इन सौर सेल के प्रदर्शन में काफी

सुधार करते हैं। इसके अलावा, हम सक्रिय परत में विभिन्न इंडियम मात्राओं के लिए InGaN सौर सेल पर एकल और दोहरे नैनोकणों के प्रभाव की जांच करते हैं और प्रदर्शित करते हैं कि अधिक इंडियम मात्रा के InGaN सौर सेल के लिए दोहरी नैनोसंरचना अधिक लाभप्रद होती है और कम इंडियम मात्रा के InGaN सौर सेल के लिए दोहरी नैनोसंरचना कम फायदेमंद होती है। इसके अलावा, हम परोक्ष प्रकाश की घटनाओं के तहत विभिन्न प्लास्मोनिक और फोटोनिक नैनोसंरचना युक्त इंडियम-समृद्ध InGaN सौर सेल के प्रदर्शन का अध्ययन करते हैं।

थीसिस के बाद के हिस्से में सौर सेल के पीछे की ओर प्लास्मोनिक नैनोसंरचनाओं के आवधिक सरणी को नियोजित करके माइक्रोक्रीस्टलाइन सिलिकॉन पतली-फिल्म सौर सेल के बेहतर प्रदर्शन का एक संख्यात्मक अध्ययन किया गया है। फिर हम दिखाते हैं कि इन प्लास्मोनिक नैनोसंरचना सरणियों के कारन प्रकाश की लम्बी तरंग दैर्घ्यों का अवशोषण बढ़ जाता है, जहां अधिकांश प्रकाश माइक्रोक्रीस्टलाइन सिलिकॉन पदार्थ के अत्यधिक कम अवशोषण गुणांक के कारण अनवशोषित रहता है। हम प्रदर्शित करते हैं कि सेल के प्रदर्शन में वृद्धि सक्रिय परत में विद्युत चुम्बकीय क्षेत्रों के बढ़ने के कारण होती है जो कि इन लंबे तरंगदैर्घ्यों पर सतह प्लास्मोन अनुनाद पर आधारित प्रकाश के प्रकीर्णन और वेवगाइड मोड के कारण होता है।

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