

WIDEBAND LEAD-FREE PIEZOELECTRIC MEMS ENERGY HARVESTING DEVICES

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DEPARTMENT OF ELECTRICAL ENGINEERING
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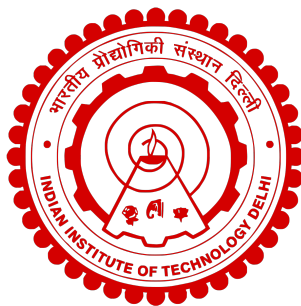
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DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

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to the



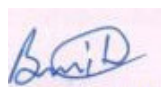
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Certificate from Advisor

This is to certify that the thesis entitled, **Wideband Lead-Free Piezoelectric MEMS Energy Harvesting Devices** being submitted by **Ms. Nitika Batra** to IIT Delhi, is worthy of consideration for the award of **Doctor of Philosophy** 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.



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Abstract

This dissertation work investigates various geometric design strategies for increasing the energy output of micro-electro mechanical systems (MEMS) cantilever based piezoelectric energy harvesting (PEH) devices along with the development of a novel lead-free environment friendly piezoelectric composite material (PVDF-TrFE/KNN). The design and configuration of the introduction of a simple geometric notch in a traditional rectangular cantilever beam for energy harvesting is investigated through parametric study, where a conventional rectangular cantilever beam with proof mass is compared with half-sine arc-shape notched cantilever beam via finite elemental simulations and also devices are fabricated as a proof of concept. The effect of the position, length, and depth of the arc on the performance of the device is studied and documented. Maximum stress, beam bending, frequency, electric output power and surface charge of the two designs are compared. For the designed cantilever beam, results showed a 9.2% decrease in maximum stress, which translates into $\sim 47.72\%$ increase in the harvested power with a slight decrease of 2.12% in the resonant frequency of the fabricated structure. As a proof of concept, PVDF-TrFE polymeric piezoelectric material was employed for the cantilever based energy harvesting device fabrication and the fabricated devices were characterized simultaneously.

Additional concepts of physical mechanical coupling of the cantilever beams in a linear configuration was employed using long and thin spring like structures to increase the bandwidth has also been studied in the context of broadband energy harvesting. The outcomes of designing uni-beam, dual-beam, tri-beam, and quad-beam coupled energy harvesters are

compared using COMSOL. Simulation results indicated that quad-beam coupled energy harvesters had a bandwidth of 11 Hz. Physical devices were fabricated as a proof of concept. Similarly, circular symmetry for mechanical coupling has been investigated using finite element simulations.

In the end, a novel lead-free piezoelectric composite material comprising of sodium potassium niobate (KNN) sol in an organic piezoelectric polymer (PVDF-TrFE) has been developed for application in energy harvesting and a flexible energy harvesting device has been demonstrated. The composite material characterized using piezoresponse force microscopy (PFM) measured an electromechanical coupling coefficient of $d_{33}=100$ pm/V. The purpose of adopting KNN sol instead of highly piezo-active KNN ceramic powder has been discussed in detail with material characterization as a function of loading ratio. The current study demonstrated the possibility of application of this composite by fabricating a flexible energy harvesting device which generate ($V_{oc}=2.2$ V) when compared to PVDF-TrFE based devices ($V_{oc}=0.05$ V). The addition of piezoactive amorphous KNN sol in moderate amount to piezoelectric polymer PVDF-TrFE tends to enhance the physical and chemical properties of the composite to a certain extent. The addition of KNN contributes towards higher film stiffness (Youngs' mod composite = 165.68 MPa and PVDF-TrFE = 161.8 MPa) and better piezoelectric coupling coefficient ($d_{33}=100$ pm/V for composite and $d_{33}=28$ pm/V for PVDF-TrFE), but also increases surface roughness and adhesion force (0.23 nN for composite and 0.15 nN for PVDF-TrFE). Further, the developed composite material performed better when compared with the literature.

In summary, the present dissertation work contains the design, fabrication, and testing of traditional and notched cantilever energy harvester. In the course of this work the concept of coupled beam energy harvesters has been explored both experimentally and by simulation methods. The exploration and characterization of a low-temperature, lead-free piezoelectric composite materials has been performed and a flexible energy harvesting device have been fabricated as a part of this dissertation.

सार

यह शोध प्रबंध माइक्रो-इलेक्ट्रो मैकेनिकल सिस्टम (MEMS) कैंटिलीवर आधारित पीजोइलेक्ट्रिक एनर्जी हार्वेस्टिंग (PEH) उपकरणों के ऊर्जा उत्पादन को बढ़ाने के लिए विभिन्न ज्यामितीय डिजाइन दृष्टिकोण की जांच करता है, साथ ही एक उपन्यास सीसा रहित पर्यावरण अनुकूल पीजोइलेक्ट्रिक कम्पोजिट सामग्री (PVDF-TrFE/KNN)। ऊर्जा संचयन के लिए एक पारंपरिक आयताकार कैंटिलीवर बीम में एक साधारण ज्यामितीय पायदान की शुरुआत के डिजाइन और विन्यास की जांच पैरामीट्रिक अध्ययन के माध्यम से की जाती है, जहां प्रूफ मास के साथ एक पारंपरिक आयताकार कैंटिलीवर बीम की तुलना हाफ-साइन आर्क-शेप नॉटेड कैंटिलीवर बीम से परिमित के माध्यम से की जाती है। तात्विक सिमुलेशन और डिवाइस भी अवधारणा के प्रमाण के रूप में निर्मित होते हैं। डिवाइस के प्रदर्शन पर आर्क की स्थिति, लंबाई और गहराई के प्रभाव का अध्ययन और दस्तावेजीकरण किया गया है। अधिकतम तनाव, बीम बेंडिंग, फ्रीक्वेंसी, इलेक्ट्रिक आउटपुट पावर और दो डिजाइनों के सरफेस चार्ज की तुलना की जाती है। डिजाइन किए गए कैंटिलीवर बीम के लिए, परिणामों ने अधिकतम तनाव में 9.2% की कमी दिखाई, जो कि निर्मित संरचना की गुंजयमान आवृत्ति में 2.12% की मामूली कमी के साथ कटाई की शक्ति में 47.72% की वृद्धि में बदल जाती है। अवधारणा के प्रमाण के रूप में, PVDF-TrFE पॉलिमरिक पीजोइलेक्ट्रिक सामग्री को कैंटिलीवर आधारित ऊर्जा संचयन उपकरण निर्माण के लिए नियोजित किया गया था और निर्माण उपकरणों को एक साथ चित्रित किया गया था।

एक रेखीय विन्यास में कैंटिलीवर बीम के भौतिक यांत्रिक युग्मन की अतिरिक्त अवधारणाओं को बेंडविड्थ बढ़ाने के लिए लंबी और पतली वसंत जैसी संरचनाओं का उपयोग करके ब्रॉडबैंड ऊर्जा संचयन के संदर्भ में भी अध्ययन किया गया है। यूनी-बीम, डुअल-बीम, ट्राई-बीम और क्वाड-बीम युग्मित एनर्जी हार्वेस्टर डिजाइन करने के परिणामों की तुलना COMSOL के उपयोग से की जाती है। अनुकार परिणामों ने संकेत दिया कि क्वाड-बीम युग्मित ऊर्जा हार्वेस्टर की बेंडविड्थ 11 Hz थी। भौतिक उपकरणों को अवधारणा के प्रमाण के रूप में बनाया गया था। इसी तरह, परिमित तत्व सिमुलेशन का उपयोग करके यांत्रिक युग्मन के लिए परिपत्र समरूपता की जांच की गई है।

अंत में, एक जैविक पीजोइलेक्ट्रिक पॉलीमर (PVDF-TrFE) में सोडियम पोटेशियम नियोबेट (KNN) सोल से युक्त एक उपन्यास सीसा रहित पीजोइलेक्ट्रिक मिश्रित सामग्री को ऊर्जा संचयन में उपयोग के लिए विकसित किया गया है और एक लचीली ऊर्जा संचयन उपकरण का प्रदर्शन किया गया है। पीज़ोरेस्पॉंस फ़ोर्स माइक्रोस्कोपी (PFM) का उपयोग करने वाली समग्र सामग्री ने $d_{33}=100$ pm/V के इलेक्ट्रोमैकेनिकल कपलिंग गुणांक को मापा। अत्यधिक पीजो-सक्रिय केएनएन सिरेमिक पाउडर के बजाय केएनएन सोल को अपनाने के उद्देश्य पर लोडिंग अनुपात के कार्य के रूप में सामग्री लक्षण वर्णन के साथ विस्तार से चर्चा की गई है। वर्तमान अध्ययन ने PVDF-TrFE आधारित उपकरणों ($V_{oc} = 0.05V$) की तुलना में ($V_{oc} = 2.2$ V) उत्पन्न करने वाले लचीले ऊर्जा संचयन उपकरण को बनाकर इस समग्र के अनुप्रयोग की संभावना का प्रदर्शन किया। पीजोइलेक्ट्रिक पॉलीमर PVDF-TrFE के लिए मध्यम मात्रा में पीजोएक्टिव अनाकार KNN सोल के अलावा समग्र के भौतिक और रासायनिक गुणों को कुछ हद तक बढ़ाता है। केएनएन का जुड़ाव उच्च फिल्म कठोरता (यंग्स मॉड कंपोजिट = 165.68 MPa और पीवीडीएफ-ट्रफ = 161.8 MPa) और बेहतर पीजोइलेक्ट्रिक कपलिंग गुणांक $d_{33}=100$ pm/V, समग्र के लिए योगदान देता है, और $d_{33}=28$ pm/V, PVDF-TrFE के लिए), लेकिन सतह खुरदरापन और आसंजन बल भी बढ़ाता है (समग्र के लिए 0.23 nN और PVDF-TrFE के लिए 0.15 nN)। इसके अलावा, विकसित समग्र सामग्री ने साहित्य की तुलना में बेहतर प्रदर्शन किया।

सारांश में, वर्तमान निबंध कार्य में पारंपरिक और नोकदार कैंटिलीवर एनर्जी हारवेस्टर का डिज़ाइन, निर्माण और परीक्षण शामिल है। इस कार्य के दौरान युग्मित बीम ऊर्जा हारवेस्टर की अवधारणा को प्रयोगात्मक और अनुकरण विधियों दोनों द्वारा खोजा गया है। एक कम तापमान, सीसा रहित पीजोइलेक्ट्रिक कम्पोजिट सामग्री की खोज और लक्षण वर्णन किया गया है और इस शोध प्रबंध के एक हिस्से के रूप में एक लचीली ऊर्जा संचयन उपकरण का निर्माण किया गया है।

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