ELECTROPLATED BISTABLE MEMS ACTUATOR USING BEOL COMPATIBLE PROCESS AND TUNING OF RESIDUAL STRESS

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by

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Department Of Electrical Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

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DEDICATION

To my beloved husband and family

CERTIFICATE

This is to certify that the thesis titled **Electroplated Bistable MEMS Actuator using BEOL Compatible Process and Tuning of Residual Stress**, submitted by **Ms. Vasudha Agrawal** to the Department of Electrical Engineering, Indian Institute of Technology Delhi is worthy of consideration for the award of the degree of **Doctor of Philosophy** and is a record of bonafide work done by her under my supervision and guidance. 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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Date: July 31, 2023

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Vasudha Agrawal

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ABSTRACT

KEYWORDS: UV LIGA ; Residual stress; Electroplating; Bistability; Latching; Lorentz force actuation; Hollow beam.

A Laterally driven copper Electroplated, initially curved bi-stable MEMS actuator is designed and fabricated with optimized electroplating parameters which can be used as a switch. The main challenge of the design is to control stress and reduce actuation voltage. This will be achieved by utilizing a curved fixed-fixed beam design. The bistable mechanism ensures that the device does not have static power consumption. Structures can be lithographically defined using lateral structure instead of the normal out-of-plane structure. Further, lateral switches lend themselves to much more complex arrays of switches. The beam is fabricated using a UV-LIGA process, using electroplated copper as the structural material and photoresist as the sacrificial layer. Recent advances in damascene electroplating and TSV technology have opened the doors for nanostructures that can be made by electroplating alone.

A key challenge here is controlling the film stress during deposition and in use. To achieve these, this work explores the effect of plating parameters to tune residual stress in the microstructure fabricated using UV-LIGA process. The electroplating parameters are optimized by varying the reverse plating current period and plating bath temperature to see the variation in the stress. Furthermore, the measured stress for different electroplating parameters is compared to see the effect of parameters on plating. It is discovered that these parameters significantly influenced the microstructure of Cu films and residual stress induced in the film. Stress developed during fabrication is measured by micro-strain gauge test structures rather than XRD, wafer curvature method, PL-Raman as this is the most accurate method from a device point of view. The fabricated initially curved bistable structure is actuated by Lorentz force using NdFeb Magnet, which gives an actuation voltage of less than 5 volts. An electrostatically actuated hollow beam has also been designed and simulated. The switching voltage and latching mechanism of curved shape latched hollow beam subjected to electrostatic force has been investigated using a reduced order model have been derived and validated against a FEM model. A 4X reduction in switching voltage is obtained from a solid bistable MEMS beam, which is actuated electrostatically. The problems encountered during fabrication are also discussed.

सार

एक पार्श्व संचालित कॉपर इलेक्ट्रोप्लेटेड, प्रारंभिक रूप से वक्र द्वि-स्थिर माइक्रो-इलेक्ट्रोमैकेनिकल सिस्टम (एमईएमएस) माइक्रोबीम को अनुकूलित इलेक्ट्रोप्लेटिंग मापदंडों के साथ डिजाइन और निर्मित किया गया है जिसे स्विच के रूप में उपयोग किया जा सकता है। डिज़ाइन की मुख्य चुनौती दबाव को नियंत्रित करना और एक्चुएशन वोल्टेज को कम करना है। यह वक्र फिक्स्ड-फिक्स्ड बीम डिज़ाइन का उपयोग करके हासिल किया जाएगा। बिस्टेबल तंत्र यह सुनिश्चित करता है कि डिवाइस में स्थिर बिजली की खपत न हो। सामान्य आउट-ऑफ-प्लेन संरचना के बजाय पार्श्व संरचना का उपयोग करके संरचनाओं को लिथोग्राफिक रूप से परिभाषित किया जा सकता है। इसके अलावा, पार्श्व स्विच स्वयं को स्विचों की अधिक जटिल श्रृंखलाओं के लिए उधार देते हैं। बीम को UV-LIGA प्रक्रिया का उपयोग करके निर्मित किया जाता है, जिसमें संरचनात्मक सामग्री के रूप में इलेक्ट्रोप्लेटेड तांबे और बलिदान परत के रूप में फोटोरेसिस्ट का उपयोग किया जाता है। डेमासीन इलेक्ट्रोप्लेटिंग और टीएसवी तकनीक में हालिया प्रगति ने नैनोस्ट्रक्चर के लिए दरवाजे खोल दिए हैं जिन्हें अकेले इलेक्ट्रोप्लेटिंग द्वारा बनाया जा सकता है।

यहां एक प्रमुख चुनौती निक्षेप और उपयोग के दौरान फिल्म दबव को नियंत्रित करना है। इन्हें प्राप्त करने के लिए, यह कार्य यूवी-एलआईजीए प्रक्रिया का उपयोग करके निर्मित माइक्रोस्ट्रक्चर में अवशिष्ट डबाव को ट्यून करने के लिए चढ़ाना मापदंडों के प्रभाव का पता लगाता है। दबाव में भिन्नता देखने के लिए इलेक्ट्रोप्लेटिंग मापदंडों को रिवर्स प्लेटिंग वर्तमान अवधि और प्लेटिंग घोल तापमान को अलग करके अनुकूलित किया जाता है। इसके अलावा, प्लेटिंग पर मापदंडों के प्रभाव को देखने के लिए विभिन्न इलेक्ट्रोप्लेटिंग मापदंडों के लिए मापा तनाव की तुलना की जाती है। यह पता चला है कि इन मापदंडों ने तांबे की फिल्मों की सूक्ष्म संरचना और फिल्म में प्रेरित अवशिष्ट तनाव को महत्वपूर्ण रूप से प्रभावित किया है। निर्माण के दौरान विकसित तनाव को एक्सआरडी, वेफर वक्रता विधि, पीएल-रमन के बजाय माइक्रो-स्ट्रेन गेज परीक्षण संरचनाओं द्वारा मापा जाता है क्योंकि यह डिवाइस के दृष्टिकोण से सबसे सटीक विधि है। प्रारंभ में निर्मित घुमावदार बिस्टेबल संरचना को एनडीएफईबी चुंबक का उपयोग करके लोरेंत्ज़ बल द्वारा सक्रिय किया जाता है, जो 5 वोल्ट से कम का एक्चुएशन वोल्टेज देता है। एक इलेक्ट्रोस्टैटिकली सक्रिय खोखले बीम को भी डिजाइन और सिम्युलेटेड किया गया है। इलेक्ट्रोस्टैटिक बल के अधीन घुमावदार आकार की कुंडीदार खोखली बीम के स्विचिंग वोल्टेज और लैचिंग तंत्र की जांच एक कम ऑर्डर मॉडल (ROM) का उपयोग करके की गई है और इसे FEM मॉडल का उपयोग करके मान्य किया गया है। स्विचिंग वोल्टेज में 4X की कमी एक ठोस बिस्टेबल एमईएमएस बीम से प्राप्त की जाती है, जो इलेक्ट्रोस्टैटिक रूप से सक्रिय होती है। निर्माण के दौरान आने वाली समस्याओं पर भी चर्चा की गई।

TABLE OF CONTENTS

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LIST OF TABLES

LIST OF FIGURES

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ABBREVIATIONS

APDL	Ansys Parametric Design Language
BEOL	Back end of line
CMOS	Complementary Metal-Oxide-Semiconductor
CTE	Coefficient of Thermal Expansion
CRF	Central Research Facility
DMSO	Dimethyl sulfoxide
DUT	Device under test
FEM	Finite Element Method
JGB	Janus Green B
LIGA	Lithography Galvanoforming Abformung
MEMS	Micro Electro Mechanical System
NRF	Nano Research Facility
NMP	N-Methyl-2-pyrrolidone
PRP	Pulse Reverse Plating
PGMEA	Propylene glycol methyl ether acetate
PEG	Polyethylene glycol
ROM	Reduced Order Modelling
SPS	bis(sodiumsulfopropyl)disulfide
RIE	Reactive Ion Etching
TSV	Through silicon via
XRD	X-ray Differaction