Microsystem Technologies 4 (1998) 168–171 © Springer-Verlag 1998

SLIGA Based underwater weapon safety and arming system

L. Fan, H. Last, R. Wood, B. Dudley, C. Khan Malek, Z. Ling

Abstract The Naval Surface Warfare Center, Indian Head Division (NSWCIHD) is applying microelectromechanical system (MEMS) technology to underwater weapon Safety and Arming (S&A) system development. MEMS technology provides an opportunity to develop a miniaturized S&A system that is more sophisticated with improved safety and reliability at a lower cost compared to current systems. An S&A system prevents premature initiation of the weapon while reliably ensuring initiation at the appropriate time. An S&A system uses multiple sensors and devices. In comparison with other weapon S&A systems, a critical aspect of underwater weapon S&A systems is the mechanical interlock system utilizing actuators and mechanical sensors. This paper describes the design, development and fabrication of S&A SLIGA device prototypes and of a SLIGA based S&A system. NSWCIHD worked with members of the HI-MEMS Alliance during design, development and fabrication. Advancements achieved by the HI-MEMS Alliance and SLIGA S&A design issues are discussed.

1
Introduction

NSWCIHD is applying MEMS technology to underwater weapon S&A system development. A MEMS S&A system potentially may be more sophisticated with increased reliability and safety while having lower cost compared to current underwater weapon S&A systems. An S&A system must sense two unique post launch environments, detect that the weapon reaches a safe separation distance from the launch platform, arm the weapon and initiate detonation of the weapon. Design requirements for new S&A systems include: i) smaller volume, ii) direct mechanically acting environmental sensors, and iii) direct mechanical linkages for locking and mechanical actuation. Additional system needs include an emerging industrial base to cost effectively produce quantities of precision electro-mechanical components ranging from 1000 to 10,000 systems. Production quantities for other weapons S&A systems and other military MEMS based systems could range up to 10^6.

For prototyping, SLIGA processing was used instead of other MEMS processing techniques because SLIGA permits integration of direct mechanically acting environmental sensors, actuators and direct mechanical interfaces. Due to the efforts of Professor Henry Guckel at the University of Wisconsin and the establishment of the HI-MEMS Alliance, there is an emerging SLIGA industrial base in the US. Finally, the batch fabrication potential for SLIGA affords similar advantages as other MEMS processes in reduced prototyping and production costs. The potential modularity and reduced production costs should yield lower in-service cost, and hence, lower overall life cycle costs.

Presented in Fig. 1 is an illustration of a SLIGA based S&A. A photo of an S&A prototype is presented in Fig. 2. The nominal dimensions are 175 μm high with a base chip size of 20 mm by 20 mm. A brief HI-MEMS Alliance processing overview is given. Following this overview, SLIGA devices and structures are discussed. Experimental results, planned testing and demonstrations are presented. Finally, HI-MEMS Alliance achievements and lessons learned regarding SLIGA processing and design are discussed.

2
Processing and devices overview

2.1
HI-MEMS alliance processing overview

Presented in Fig. 3 is a HI-MEMS Alliance SLIGA fabrication process overview. This overview identifies the general process steps and the Alliance member(s) responsible for each step. A schematic illustration of the process flow is presented.

Received: *25 August 1997*/*Accepted: 10 September 1997*

L. Fan, H. Last
Naval Surface Warfare Center,
Indian Head Division, 101 Strauss Avenue, Blds. 302
Indian Head, MD 20640, USA

R. Wood, B. Dudley
MCNC MEMS Technology Application Center, RTP, NC

C. Khan Malek, Z. Ling
LSU-CAMD,
Louisiana State University
3990 West Lakeshore Drive
Baton Rouge, LA 70803, USA

Correspondence to: L. Fan

The authors acknowledge the financial support received from the Defense Advanced Projects Agency-Electronic Technologies Office (DARPA-ETO) and the Office of Naval Research (ONR). The technical support received from the other HI-MEMS Alliance members including Prof. Henry Guckel from the University of Wisconsin, IEP Group, Inc. and Oak Ridge National Laboratory is greatly appreciated. Special thanks to Don Garvick who was instrumental in establishing the MEMS S&A effort at NSWCIHD.

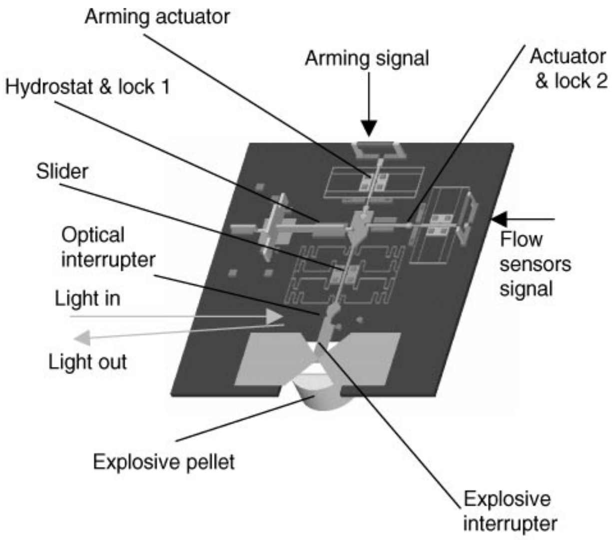

Fig. 1. Illustration of a SLIGA based S&A

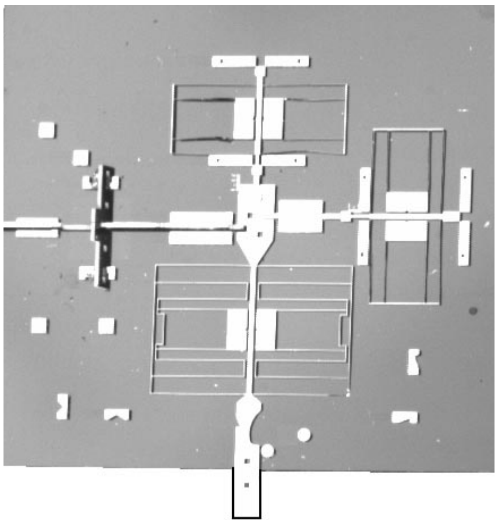

Fig. 2. Photo of SLIGA based S&A produced by HI-MEMS alliance

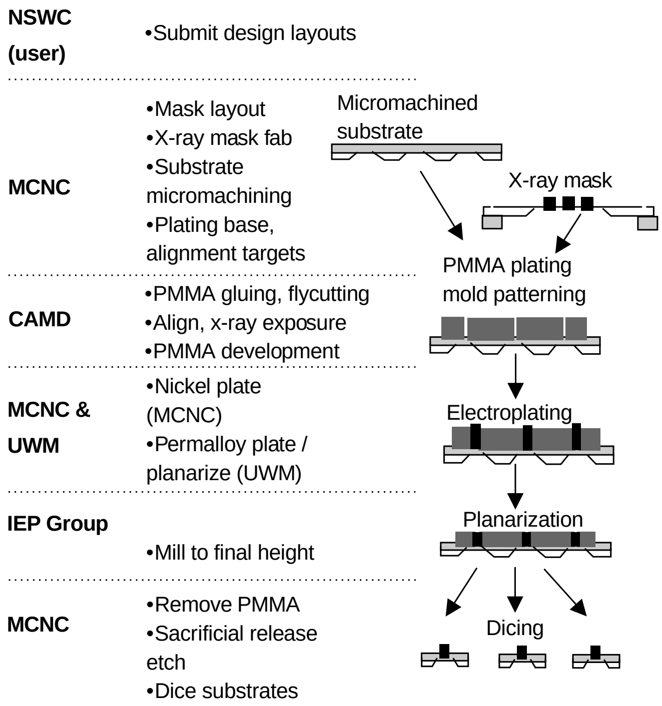

Fig. 3. HI-MEMS alliance process flow overview

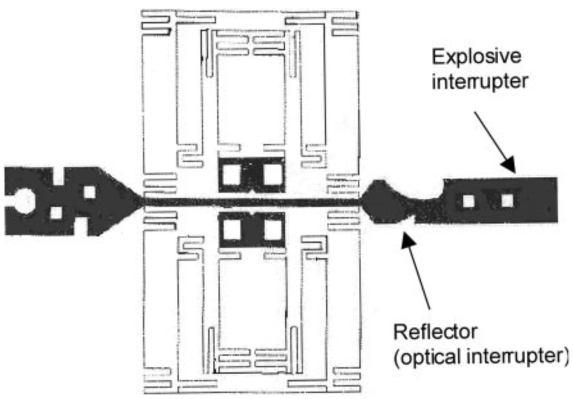

Fig. 4. Photo of SLIGA slider/interrupter

2.2
Devices overview

2.2.1
Slider/interrupter

A photo of the slider/interrupter structure is presented in Fig. 4. When the slider/interrupter is in the "safe" position as illustrated in Fig. 1, detonation of warhead will not occur. When the slider/interrupter is in the "armed" position, detonation of the warhead may occur.

In the "safe" position, this structure provides interruption of the detonation of the warhead by two methods. The first method is by physical interruption of the explosive train. The end of this structure, identified in Fig. 4, is located between two successive components in the explosive train. This barrier prevents the transmission of energy to the next component in the explosive train; therefore, preventing or "interrupting" the detonation process. In the "armed" position, this barrier is removed from between the explosive train components.

The second interruption method is provided by obstructing the charging circuit needed for charging capacitors used in the initiation of detonation of the explosive train. A reflector on the side of the slider/interrupter acts as a mirror to direct light along one of two paths. The reflector is indicated in Fig. 4. When the slider is in the "safe" position, light is not reflected into the photodiode for the charging circuit. When the slider/interrupter is in the "armed" position, light is reflected into a photodiode that is part of the charging circuit.

2.2.2
Hydrostat

The hydrostat is labeled "hydrostat & lock 1" in Fig. 1. Presented in Fig. 5 are illustrations of two designs of SLIGA hydrostats: fully released and partially released. The hydrostat is a fully mechanical pressure transducer. In the SLIGA based

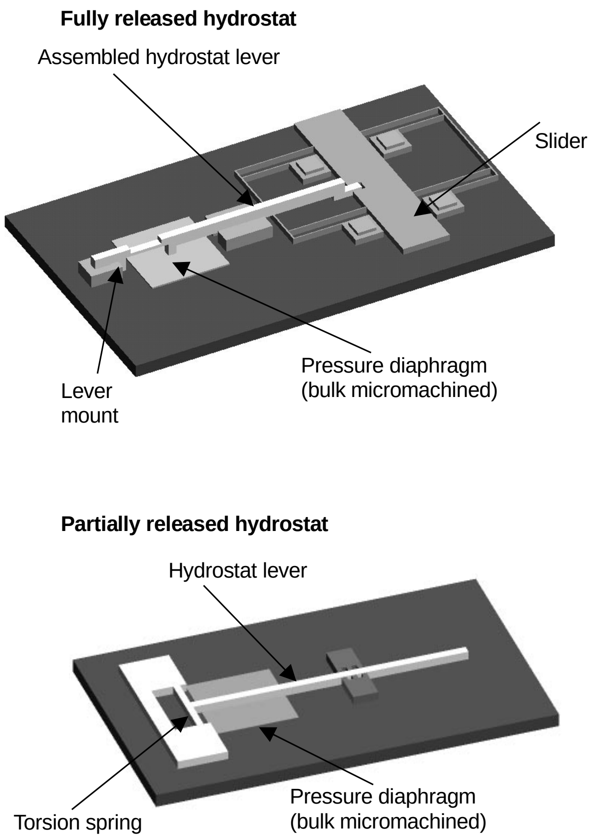

Fig. 5. Illustrations of SLIGA hydrostat designs

S&A system design, the hydrostat acts one of two required environment sensing locks on the slider/interrupter.

The diaphragm deflects when a pressure differential is applied across it. The diaphragm pushes on the lever and the lever deflects. The deflection of the lever at the diaphragm is amplified at the end of the lever. The amount of deflection amplification is controlled by the "stiffness" of the restoring spring and the length of the lever. As illustrated in Fig. 1, if no pressure differential exists across the hydrostat diaphragm, the lever interferes with the movement of the slider/interrupter effectively "locking" the slider/interrupter in the "safe" position. When a predetermined pressure differential is sensed, the end of lever deflects so that the lever is no longer "locking" the slider/interrupter.

The "fully released" hydrostat utilizes fixed structures into which the lever is assembled. The "partially released" hydrostat uses the "sacrificial etching" SLIGA approach where selected sections of a structure may be released from the substrate by sacrificial etching and other sections remain attached to the substrate. The partially released design minimizes the need for assembly. Results of laboratory based testing will be presented in a later section. Also, plans for future testing and demonstration will be discussed. This hydrostat is an NSWCIHD and MCNC designed device. A patent application has been filed for this device.

2.2.3
Arm enable actuator

This SLIGA based permalloy actuator was developed by the Professor Henry Guckel at the University of Wisconsin – Madison (UWM). This actuator is described in reference [1]. The arm enable actuator is labeled as Lock 2 in Fig. 1. This actuator is powered by a signal from a required environmental sensor. In Fig. 1, the power is supplied by a flow sensor. When a certain flow rate is sensed, the coil is energized by the signal sent from the flow sensor. The plunger of the actuator is pulled into the pole pieces and the locking end of the arm enable actuator is removed from the slider/interrupter structure. The actuator is now in the "arm enabled" position. Plans for future testing and demonstration will be discussed in a later section.

2.2.4
Arming actuator

This SLIGA based permalloy actuator also was developed by Professor Henry Guckel at UWM. The arming actuator is labeled in Fig. 1. This actuator will be a 3-stage actuator designed to provide up to 500 microns of displacement and 20 mN of force. When the coils are energized in a sequential manner, the plungers are pulled into the pole pieces displacing the spring supported structure. This actuator is mechanically interlocked via a key to the slider/interrupter structure. When the actuator is displaced, the slider/interrupter is displaced. The slider/interrupter is moved from the "safe" position to the "armed" position.

3
Test results and future plans

3.1
Slider/interrupter

The effectiveness of the slider/interrupter acting as a physical barrier to prevent transfer of energy between explosive components has been tested. Barriers made of PMMA and of nickel have been tested. Barriers of each material were acceptable. Initial optical testing of the reflecting structures is to be completed.

3.2
Hydrostat testing

Several designs of the partially released hydrostat have been tested using compressed nitrogen. Presented in Fig. 6 is an example of results plotting measured end of lever deflection as a function of applied pressure. A minimum end of lever displacement of 120 microns was observed for several partially released designs. This deflection is sufficient to "unlock" Lock #1 from the slider/interrupter. NSWC is currently fixturing the device for pressure testing using water. The assembled hydrostat design will be tested following a similar approach. The pressure testing using water and the assembled hydrostat testing will be completed.

3.3
Arm enable and arming actuator

Initial testing of a UWM supplied actuator has been completed. This testing consisted of i) applying a current through the coil and displacing the suspended spring structure and ii) manually displacing the spring structure and measuring inductance as a function of spring structure position. Testing of the arm-enable and arming actuators supplied by the HI-MEMS Alliance will be completed.

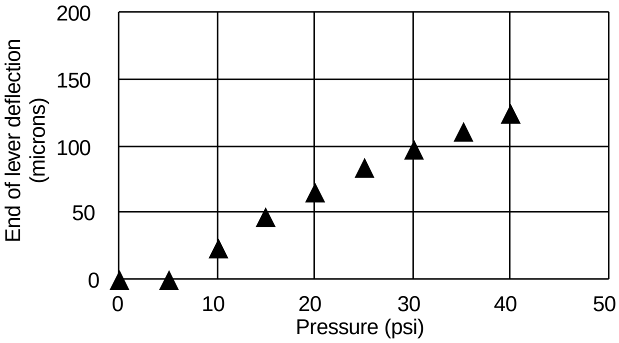

Fig. 6. End of lever deflection vs. pressure for semi-released hydrostat

In addition to functional testing of these actuators, force-displacement measurement on the spring-suspended plunger structures will be performed. This testing is based on a method developed by John Haake at McDonnell-Douglas Aerospace [2]. This method involves displacing the plunger structure using a cantilevered optical fiber of a known length. Based upon calibration of the force-deflection response of the fiber, the force applied to the plunger structure may be determined. The deflection of the plunger structure is measured using a graduated micrometer stage to which the structure has been rigidly affixed. The "stiffness" of the structure may be calculated from the force-displacement data. This data may be compared with force-displacement data obtained during functional testing and with results from finite element analysis.

3.4
Water tunnel demonstration

The functionality of a version of the SLIGA-based S&A prototype is to be demonstrated in water tunnel testing later this year. This system testing involves device functional testing, mechanical and electrical integration of the devices and other components, and overall packaging of the system. There may also be functional testing of sub-systems as needed.

4
Achievements and lessons learned

4.1
HI-MEMS alliance achievements

The achievements of the HI-MEMS Alliance made it possible to continue with the development of a SLIGA-based S&A system. The Alliance demonstrated integration of SLIGA processing with micromachining including: i) the hydrostat, ii) the IBM LIGA integrated minimotor and iii) LIGA thermal actuators driven by surface micromachined heaters. The Alliance developed X-ray alignment techniques for aligning LIGA structures on patterned substrates and for producing non-orthogonal LIGA structures using off-axis X-ray lithography. The Alliance has performed an analysis of the dimensional capability of LIGA. Also, process biases have been measured and the sources of the biases are being investigated.

4.2
SLIGA S&A design issues

Many advancements of the SLIGA processing were realized due to the lessons learned by and needs of the Alliance members. The lessons learned utilized in S&A design include
i) minimize assembly required in device design,
ii) incorporate assembly and packaging needs early in device design to utilize SLIGA in packaging and assembly (e.g., interlocking structures),
iii) update and incorporate process based design rules,
iv) evolve test methods for SLIGA structures and devices,
v) investigate suitability of standard FEA/Analysis tools for SLIGA design based on test results,
vi) material properties are needed to compare predicted results with test results.

5
Summary

The interaction of NSWCIHD with the HI-MEMS Alliance has led to the development of a SLIGA-based S&A system. The achievements of the Alliance and the lessons learned have led NSWCIHD to continue further evolution of the SLIGA-based S&A design with the Alliance.

References

Guckel H; et al.: (1996) Electromagnetic linear actuators with inductive position sensing. Sensors and Actuators A 53: 386–391

Haake J: (1997) private communication