DESIGN AND FABRICATION OF SENSORS ON FIBERS

R. Sirdeshmukh
B. Panchapakesan, A. Abu-Obaid, D. Heider

UD-CCM • 1 July 2003
1. REPORT DATE  
26 AUG 2004

2. REPORT TYPE  
N/A

3. DATES COVERED  
-

4. TITLE AND SUBTITLE  
Design And Fabrication Of Sensors On Fibers

5a. CONTRACT NUMBER  
-

5b. GRANT NUMBER  
-

5c. PROGRAM ELEMENT NUMBER  
-

5d. PROJECT NUMBER  
-

5e. TASK NUMBER  
-

5f. WORK UNIT NUMBER  
-

6. AUTHOR(S)  
-

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  
University of Delaware Center for Composite Materials Newark, DE 19716

8. PERFORMING ORGANIZATION REPORT NUMBER  
-

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  
-

10. SPONSOR/MONITOR’S ACRONYM(S)  
-

11. SPONSOR/MONITOR’S REPORT NUMBER(S)  
-

12. DISTRIBUTION/AVAILABILITY STATEMENT  
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES  
See also ADM001700, Advanced Materials Intelligent Processing Center: Phase IV., The original document contains color images.

14. ABSTRACT  
-

15. SUBJECT TERMS  
-

16. SECURITY CLASSIFICATION OF:  
a. REPORT  
unclassified

b. ABSTRACT  
unclassified

c. THIS PAGE  
unclassified

17. LIMITATION OF ABSTRACT  
UU

18. NUMBER OF PAGES  
19

19a. NAME OF RESPONSIBLE PERSON  
-

Standard Form 298 (Rev. 8-98)  
Prescribed by ANSI Std Z39-18
Overview

- **OBJECTIVE**
  - Develop *Smart Materials* through devices / sensors on fibers

- **APPROACH**
  - Materials and fabrication methods
  - Connectors and traces
  - Sensor design
    - Flow monitoring of Micro-flow
    - Strain sensor
    - Temperature (thermocouple) sensor
    - Others
  - Device design
    - Diode
    - Transistors
    - Microprocessors
Challenges

- **Connections**
  - External
  - Internal

- **Miniaturization of Sensors and Devices**
  - New concept of circular masks for printing on fibers

- **Compatibility**
  - Fiber-Device Interface
  - Device Durability
    - Composite Processing
    - In-Service (Strain, Load, Fatigue, Temperature, etc.)

- **Potential for Scale-up**
  - Continuous processing of fibers
  - SMART preforms
Materials and Methods

- **Fibers**
  - E-glass (diameter: 14µm)
  - Kevlar (diameter: 12µm)
  - Optical fiber (diameter: 250µm)

- **Photoresist**
  - Photosensitive polymeric material sensitive to i-line (365nm) and h-line (405nm) UV radiation

- **Limitations of working with a fiber tow**
  - Photoresist flows through gap between fibers, causes very uneven surfaces
Review: Micro-Device Fabrication

- Fabrication steps
  - Mask
  - Lithography
    - Coat with photoresist
    - Softbake
    - Exposure to UV light
    - Hardbake (in some cases)
    - Develop
  - Metal Deposition
  - Lift-off (of unwanted metal)
New Continuous Photoresist Coating Process

- Method of coating fiber with photo-resist
  - Cross-head frame (Instron)
  - Modification from standard spin coating system
  - Uniformity of layer:
    - Viscosity of photoresist material (lower viscosity favored)
    - Speed

- 1- Die containing photoresist
- 2- Cylindrical heater element for immediate softbake following coat

Setup developed for coating
Continuous Coating Process

Higher viscosity photoresist

Lower viscosity photoresist

E-glass Fiber coated with photoresist by conventional spin-coat method (flat pattern)
Future Work: Continuous Masking of Photoresist for Traces

- Near term future work: Implementation of continuous masking

- Bad patterns due to large gap between fiber and metal sheet
- Modification applied – sidewall of slot inclined to minimize gap by contact with fiber (analogous to contact lithography)
Challenges of Device/Sensor Fabrication on Fibers

- **Masking**
  - To use entire surface area for patterning
  - Standard mask – flat

- **Lithography**
  - To obtain accurate pattern transfer on curved surfaces
  - Non-uniform exposure due to curved shape of fiber

- **Metal Deposition and Lift-off**
  - Accuracy will prevent adhesion problems due to shape of substrate

**SOLUTION**
- Desired mask – cylindrical
Cylindrical vs. Flat Mask Geometry

**Standard flat mask**
- Used in standard microfabrication procedures
- Use of less surface area
- Curved structure – distorted images

**Cylindrical mask**
- Curve of mask corresponds to curve of substrate (fiber)
- Distortion of images reduced
- More uniform UV exposure
- Covers complete surface area
Example of Flat Mask Pattern

Proven that traces can applied to fibers, but distorted pattern due to flat mask
Solution: Cylindrical mask
Sensor Design and Development

- Three basic sensor designs developed
  - Flow monitoring
  - Temperature sensing
  - Strain sensing

- Issues with sensors on fiber
  - Reliability of device/sensor
  - Multiple connectors and traces required for measurements

- Advantages
  - Monitoring of Micro-Flow or local parameters (millimeter size) possible
  - Creation of “smart” composites
Flow Monitoring

- **Basic idea**
  - To detect position of resin within fiber tow

- **Validation of Micro-Flow Models**
  - Flow path of resin to fiber
  - State in between wet and dry stages of fiber

![Diagram showing infiltration time and ratio](image)

- Infiltration Time (seconds)
- Infiltration Ratio ($\frac{r_i}{r_o}$)

- $r_i/r_o = 1$ (Tow Empty)
- $r_i/r_o = 0$ (Tow Full)

- $\gamma = 0.0354 \text{ N/m}$
- $r_f = 3.5 \mu\text{m}$
- $\theta = 30^\circ$
- $\eta = 100 \text{ cps}$

- $60K (v_f=0.8)$
- $24K (v_f=0.8)$
- $6K (v_f=0.8)$
- $60K (v_f=0.5)$
Flow Monitoring

Preliminary designs

- Flow of resin

- Non-conducting Material

Anticipated relations:

Conductance vs. Time

Conductance vs. Time

Conductance vs. Time
Example of thermocouple temperature sensor

- Si-Al thermocouple junction
- Seebeck Coefficient of Polysilicon ($S_1$): -415.6 µV/K
- Seebeck Coefficient of Aluminum ($S_2$): -1.7 µV/K
- Sensitivity increased by increasing the number of elements

Application: monitoring local exothermic reactions (micro-kinetics)
Strain Sensor Concept

- **Theory behind piezoelectricity**
  - Mechanical stress applied on materials with non-centro symmetric crystallinity induces formation of dipoles

- **Piezoresistivity**
  - Change in resistance due to strain
  - Gauge factor:
    \[ k = \frac{d\rho}{\rho} \]
  - \( \rho \) → intrinsic resistivity of material

- **Application**
  - Residual stress measurement
  - Health monitoring of composite
  - Vibration measurement
Long Term Objectives

- Automated process to make Smart Preforms of fiber-based sensors
  - Sensors embedded within preform continuously generating and transmitting data

- Electronic devices on fibers to make circuits
  - Diodes
  - Transistors
  - Microprocessors!
Example – Diode Fabrication

➢ Simplified procedure of fabricating a GaAS P-I-N diode on fiber
Summary

- Preliminary research on sensors/devices on fibers
- Key hurdles
  - Circular masks
  - Connection to the outside world
- Evaluated photo-resist materials and developed continuous application process
- Applied successful flat mask pattern on fiber
- Developed design concepts for sensors