UNIVERSITY OF DELAWARE
CENTER FOR COMPOSITE MATERIALS
INTERNATIONALLY RECOGNIZED EXCELLENCE

OFFICE OF NAVAL RESEARCH

DESIGN AND FABRICATION OF SENSORS ON FIBERS

R. Sirdeshmukh

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

UD-CCM • 1 July 2003

Report Documentation Page

Form Approved
OMB No. 0704-0188

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

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
unclassified	**unclassified**	**unclassified**	**UU**	**19**	

Overview

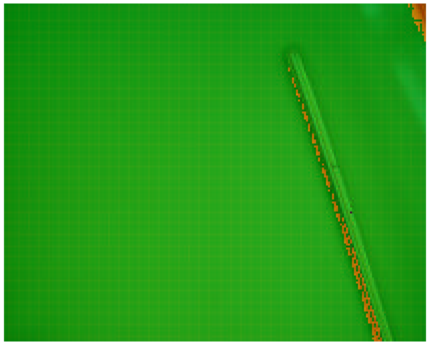
- **OBJECTIVE**
  - **Develop *Smart Materials* through devices / sensors on fibers**
- **APPROACH**
  - **Materials and fabrication methods**
  - **Connectors and traces**
  - **Sensor design**
    - Flow monitoring of Micro-flow
    - Strain sensor
    - Temperature (thermocouple) sensor
    - Others
  - **Device design**
    - Diode
    - Transistors
    - Microprocessors

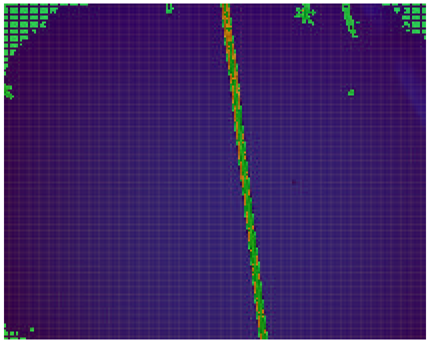
Challenges

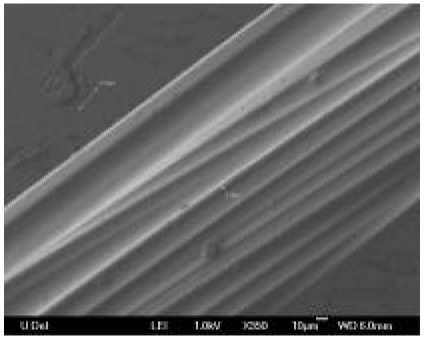
- Connections
  - External
  - Internal
- Miniaturization of Sensors and Devices
  - New concept of circular masks for printing on fibers
- Compatibility
  - Fiber-Device Interface
  - Device Durability
    - Composite Processing
    - In-Service (Strain, Load, Fatigue, Temperature, etc.)
- Potential for Scale-up
  - Continuous processing of fibers
  - SMART preforms

Materials and Methods

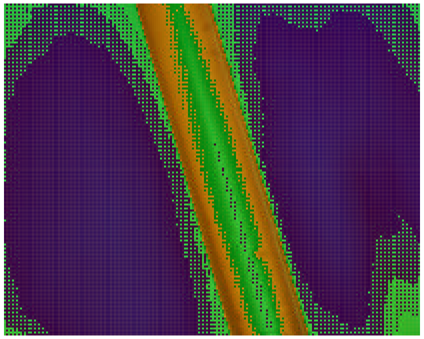
- **Fibers**
  - E-glass (diameter: 14µm)
  - Kevlar (diameter: 12µm)
  - Optical fiber (diameter: 250µm)
- **Photoresist**
  - Photosensitive polymeric material sensitive to i-line (365nm) and h-line (405nm) UV radiation
- **Limitations of working with a fiber tow**
  - Photoresist flows through gap between fibers, causes very uneven surfaces


E-glass


S2-glass

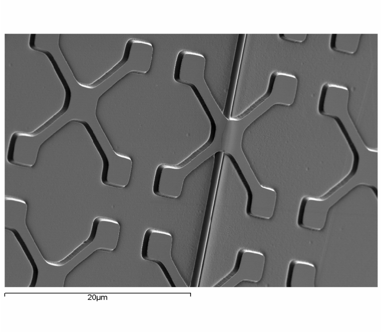

Kevlar fiber tow

Fiber tow of approximately 50 fibers coated with photoresist

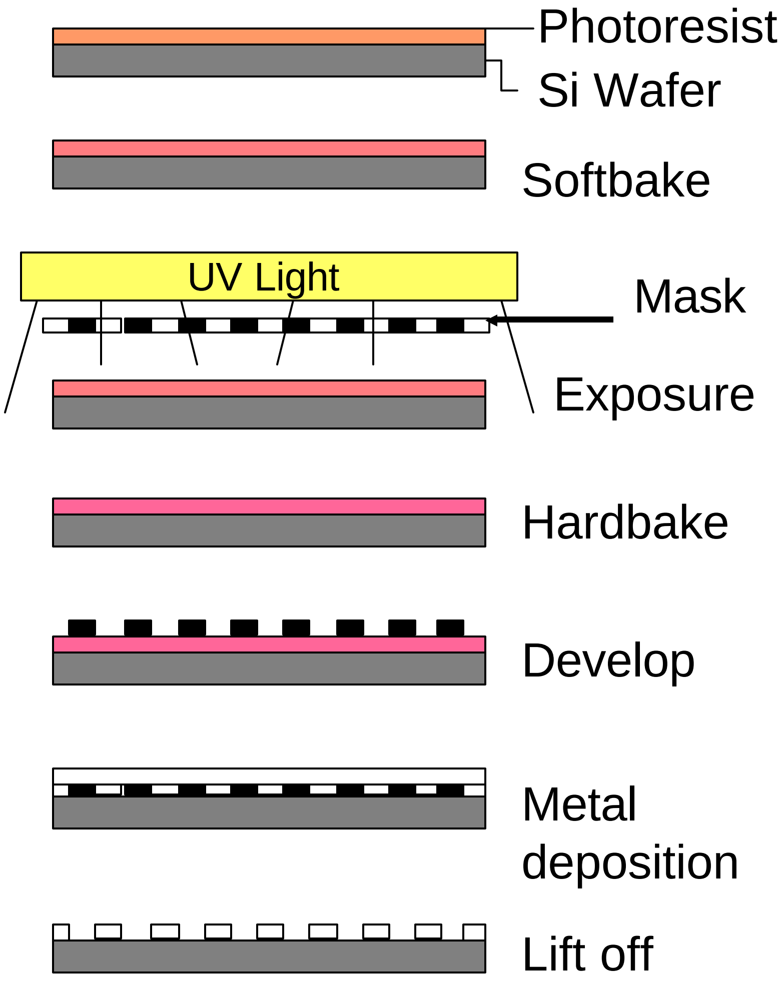

Fiber optic

Review: Micro-Device Fabrication

- **Fabrication steps**
  - **Mask**
  - **Lithography**
    - Coat with photoresist
    - Softbake
    - Exposure to UV light
    - Hardbake (in some cases)
    - Develop
  - **Metal Deposition**

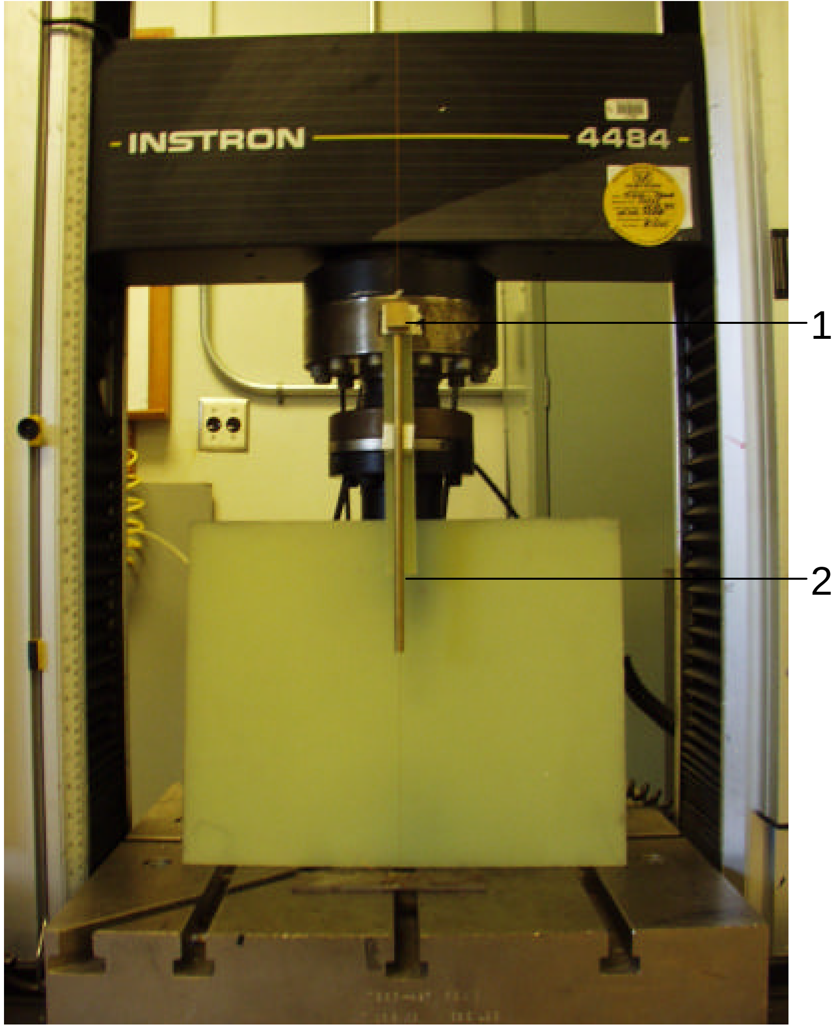


  - **Lift-off (of unwanted metal)**



New Continuous Photoresist Coating Process

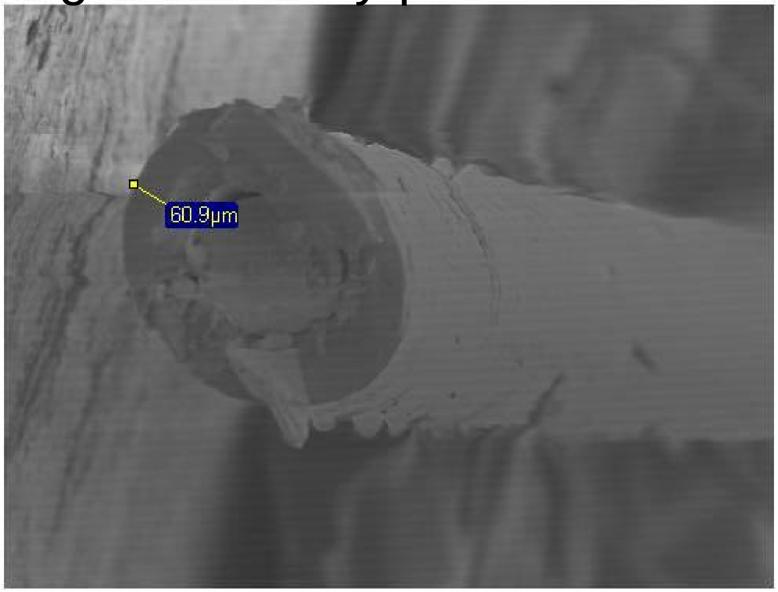
- **Method of coating fiber with photo-resist**
  - **Cross-head frame (Instron)**
  - **Modification from standard spin coating system**
  - **Uniformity of layer:**
    - Viscosity of photoresist material (lower viscosity favored)
    - Speed
- **1- Die containing photoresist**
- **2- cylindrical heater element for immediate softbake following coat**



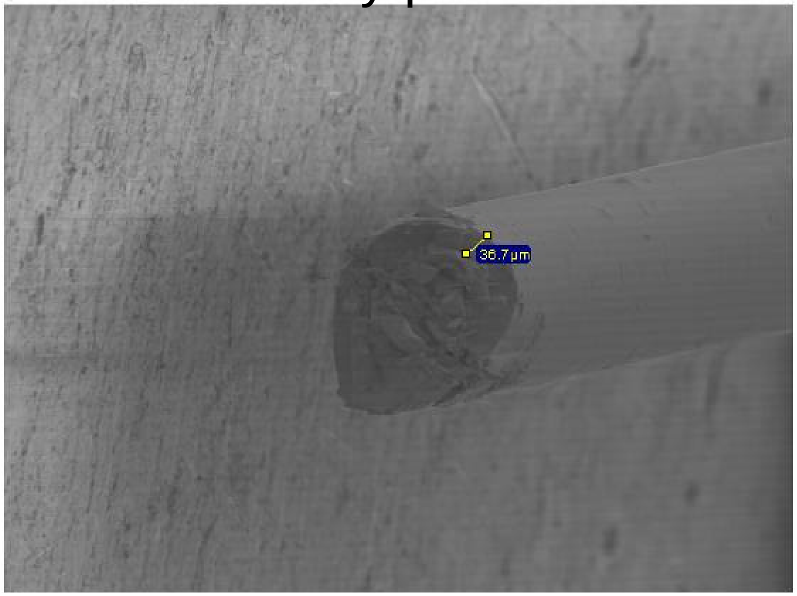
Setup developed for coating

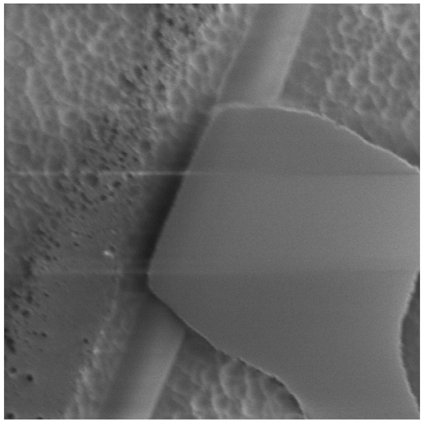
Continuous Coating Process

Higher viscosity photoresist



Lower viscosity photoresist

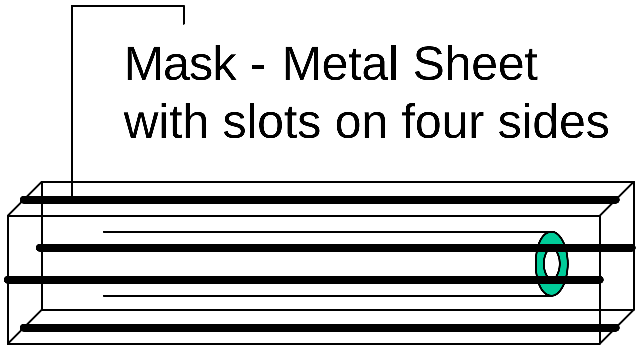




E-glass Fiber coated with photoresist by conventional spin-coat method (flat pattern)

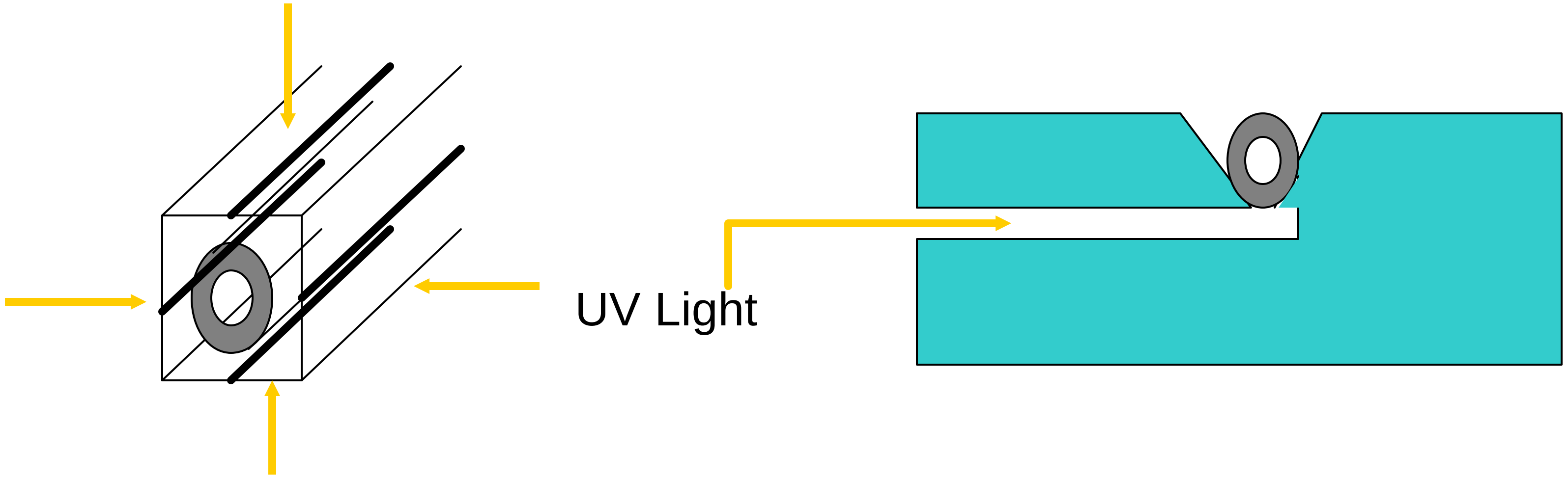
Future Work: Continuous Masking of Photoresist for Traces

- **Near term future work: Implementation of continuous masking**



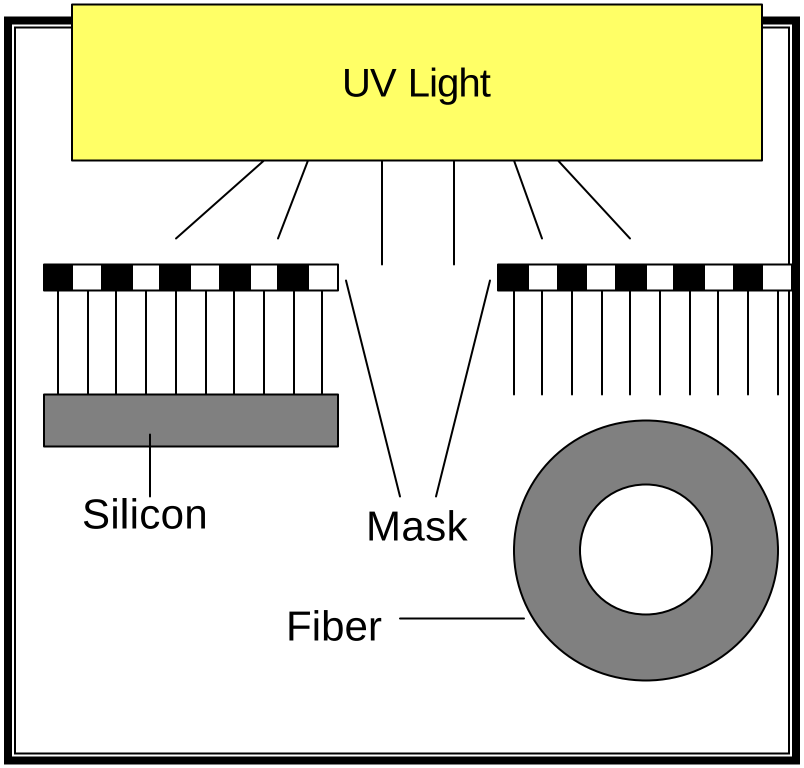
Mask - Metal Sheet with slots on four sides

- **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)**



UV Light

Challenges of Device/Sensor Fabrication on Fibers



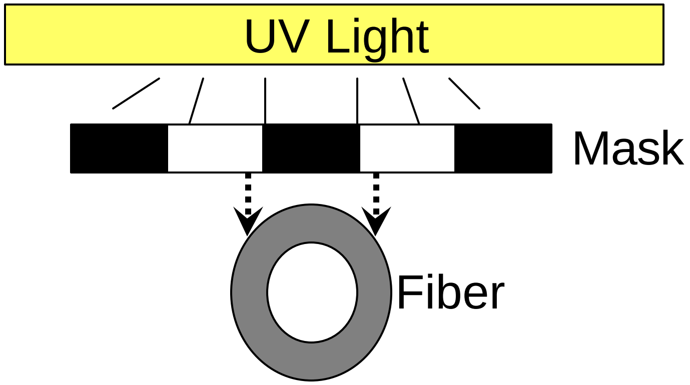
- **Masking**
  - To use entire surface area for patterning
  - Standard mask – flat
- **Lithography**
  - To obtain accurate pattern transfer on curved surfaces
  - Non-uniform exposure due to curved shape of fiber
- **Metal Deposition and Lift-off**
  - Accuracy will prevent adhesion problems due to shape of substrate

SOLUTION

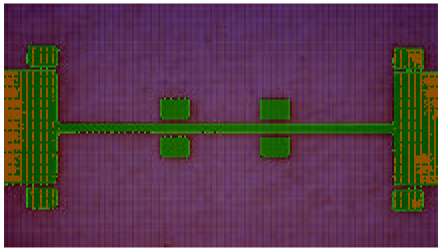
- **Desired mask – cylindrical**

Cylindrical vs. Flat Mask Geometry

Standard flat mask

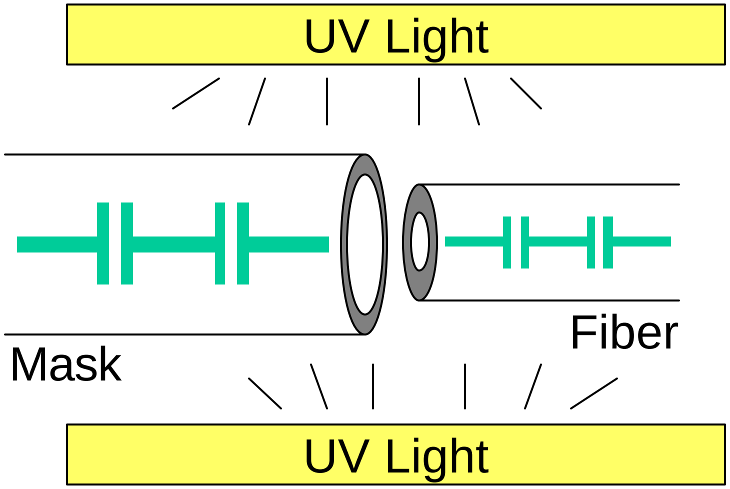


- ➢**Used in standard microfabrication procedures**
- ➢**Use of less surface area**
- ➢**Curved structure – distorted images**



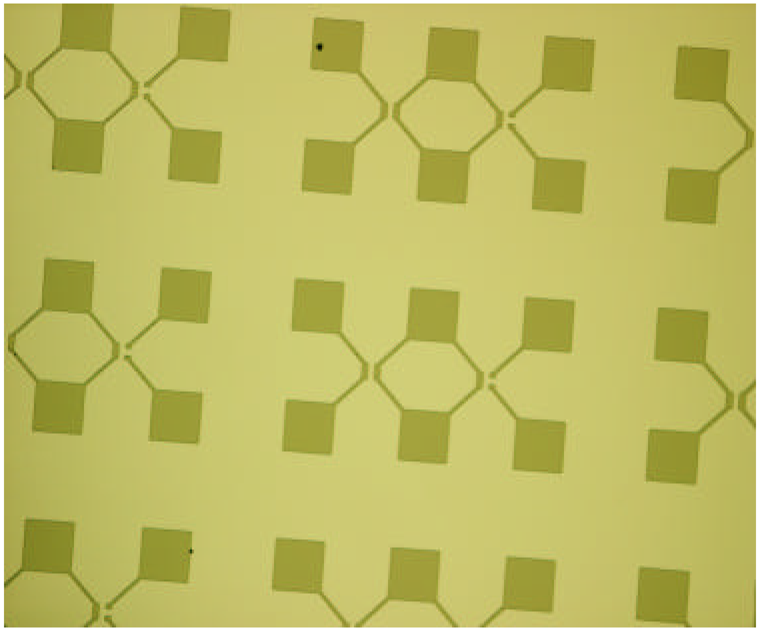
Standard Flat Mask Plate

Cylindrical mask

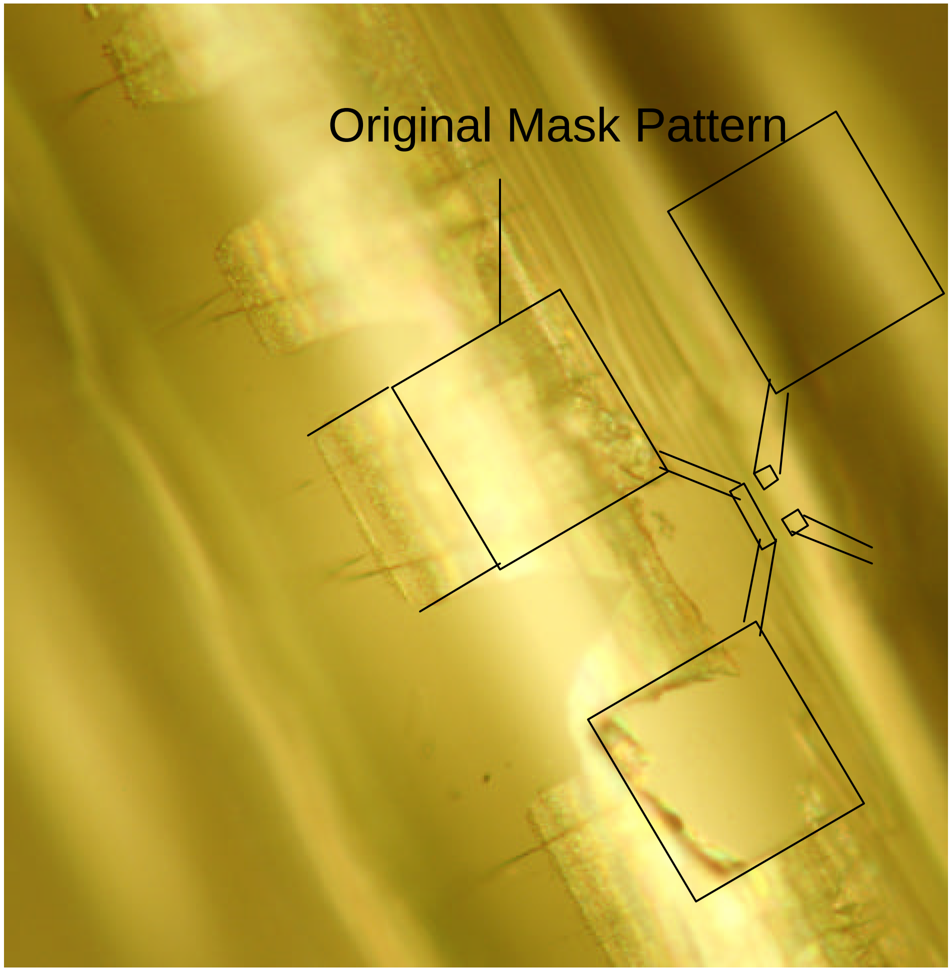


- ➢**Curve of mask corresponds to curve of substrate (fiber)**
- ➢**Distortion of images reduced**
- ➢**More uniform UV exposure**
- ➢**Covers complete surface area**

Example of Flat Mask Pattern



Applied mask pattern



Proven that traces can applied to fibers, but distorted pattern due to flat mask

Solution: Cylindrical mask

Sensor Design and Development

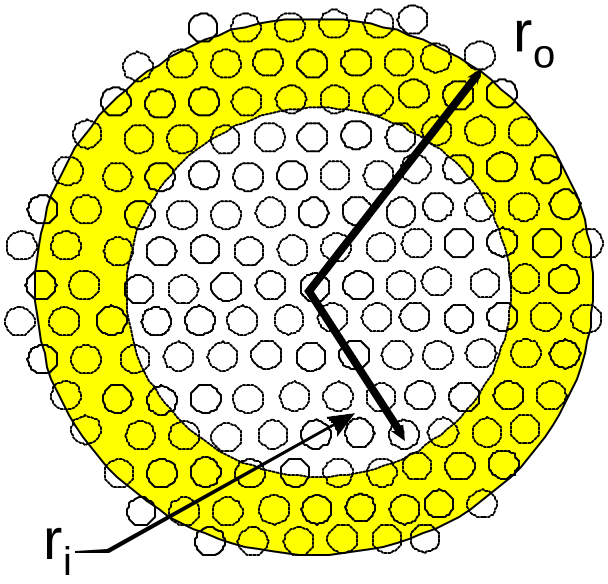
- Three basic sensor designs developed
  - Flow monitoring
  - Temperature sensing
  - Strain sensing

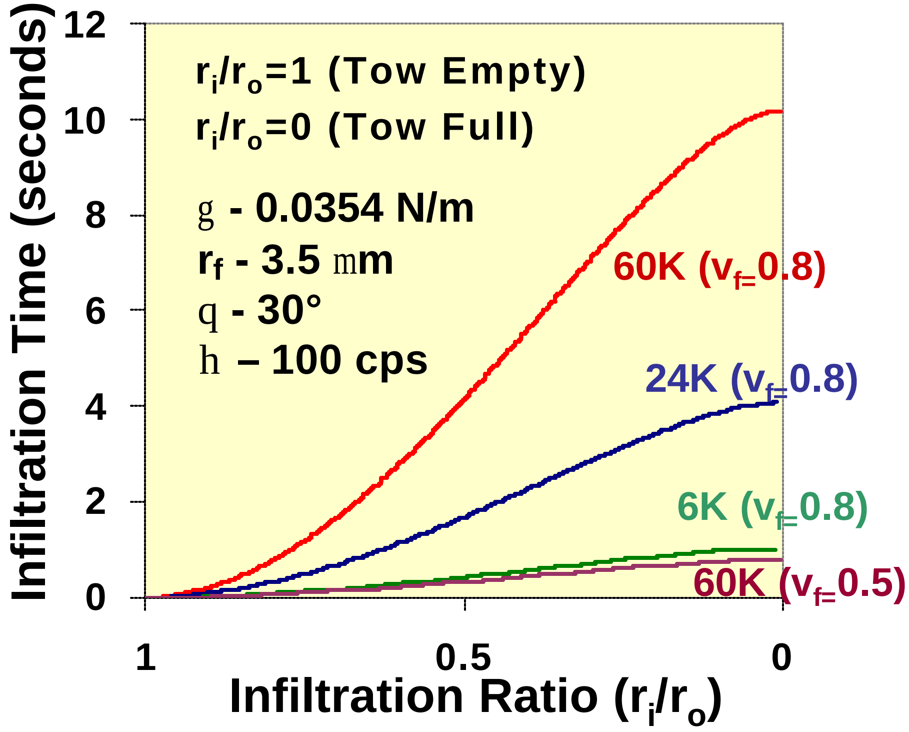
- Issues with sensors on fiber
  - Reliability of device/sensor
  - Multiple connectors and traces required for measurements

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

Flow Monitoring

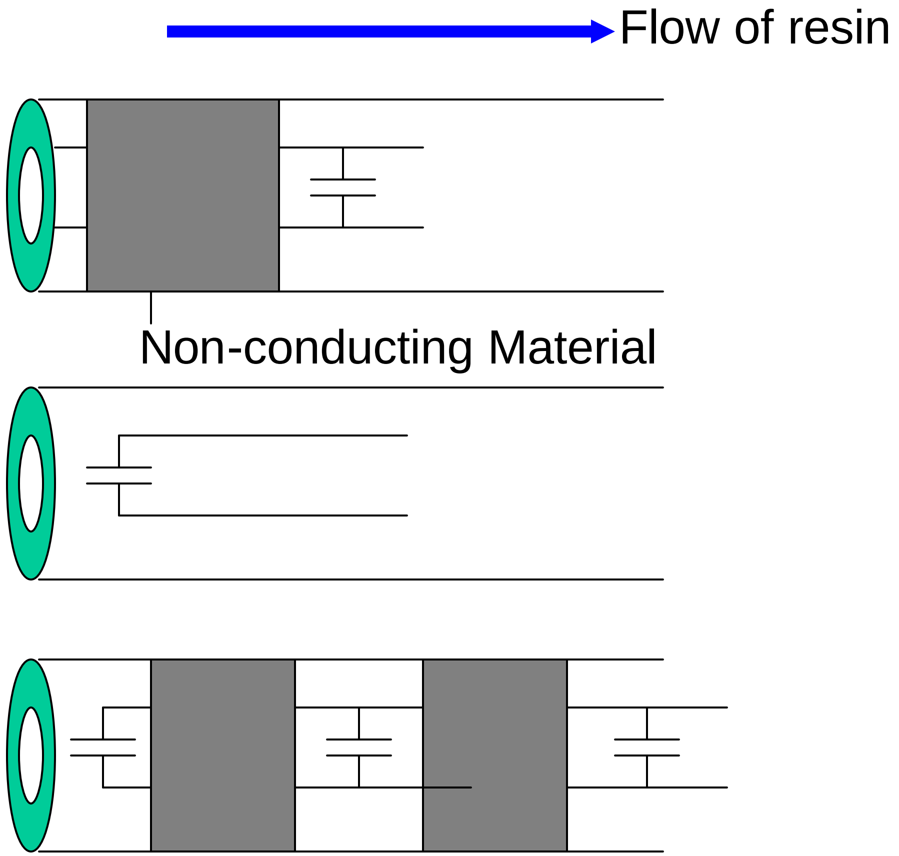
- Basic idea
  - To detect position of resin within fiber tow
- Validation of Micro-Flow Models
  - Flow path of resin to fiber
  - State in between wet and dry stages of fiber



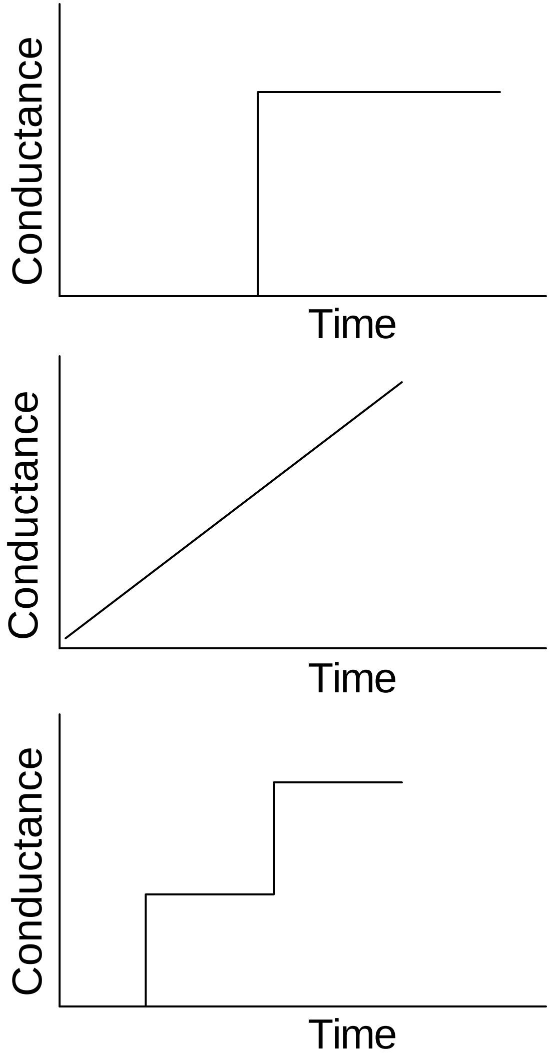


Flow Monitoring

Preliminary designs



Anticipated relations

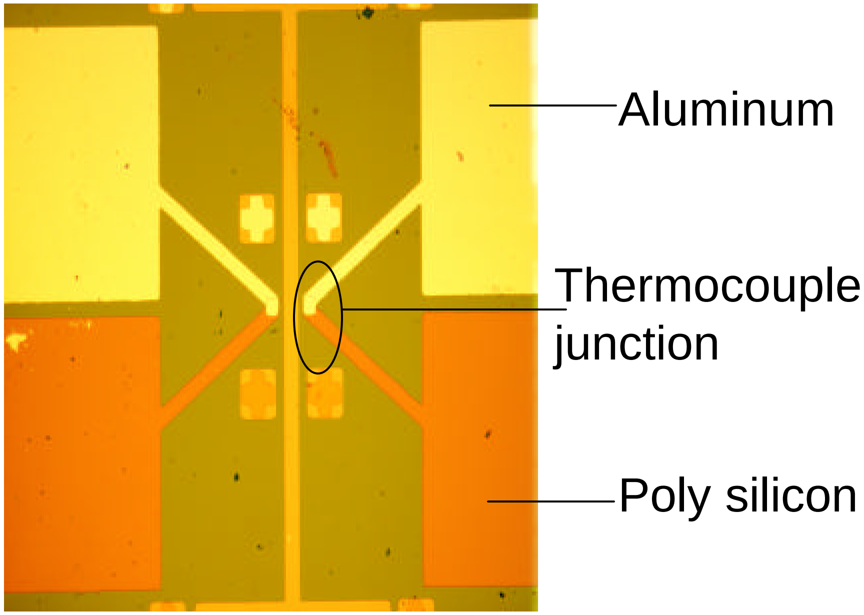


Thermocouple Temperature Sensor

- ➢ **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**

$$V = \int_{T_1}^{T_2} [S_1(T) - S_2(T)]\,dT$$

  - ✦ **Sensitivity increased by increasing the number of elements**



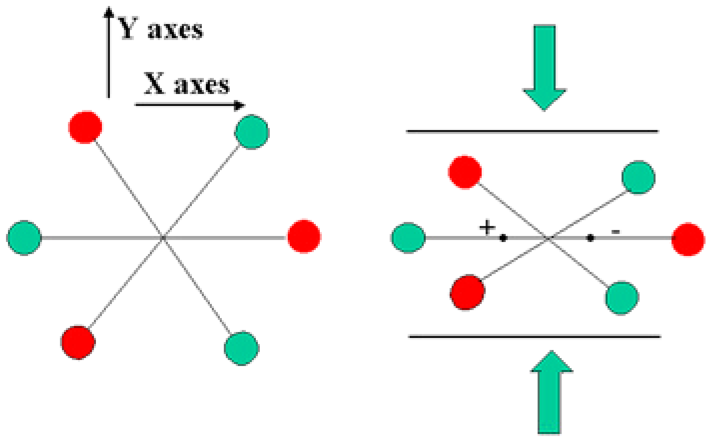
- ➢ **Application: monitoring local exothermic reactions (micro-kinetics)**

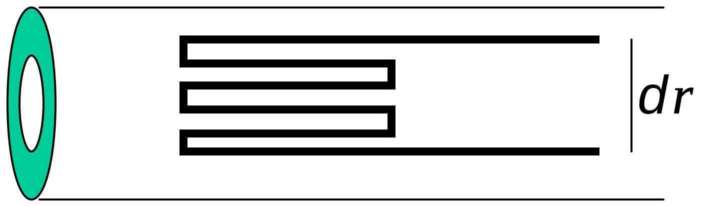
Strain Sensor Concept

- **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:

$$k = \frac{dr}{r}$$

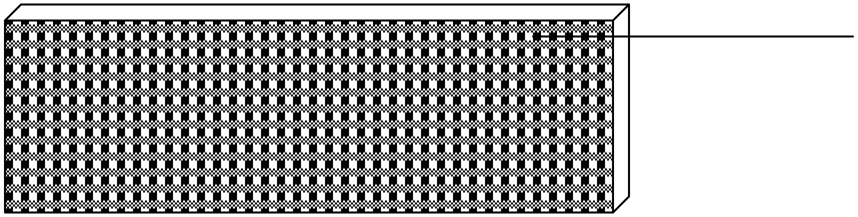
  - r ⇒ intrinsic resisitivity of material
- **Application**
  - Residual stress measurement
  - Health monitoring of composite
  - Vibration measurement





Long Term Objectives

- Automated process to make Smart Preforms of fiber-based sensors

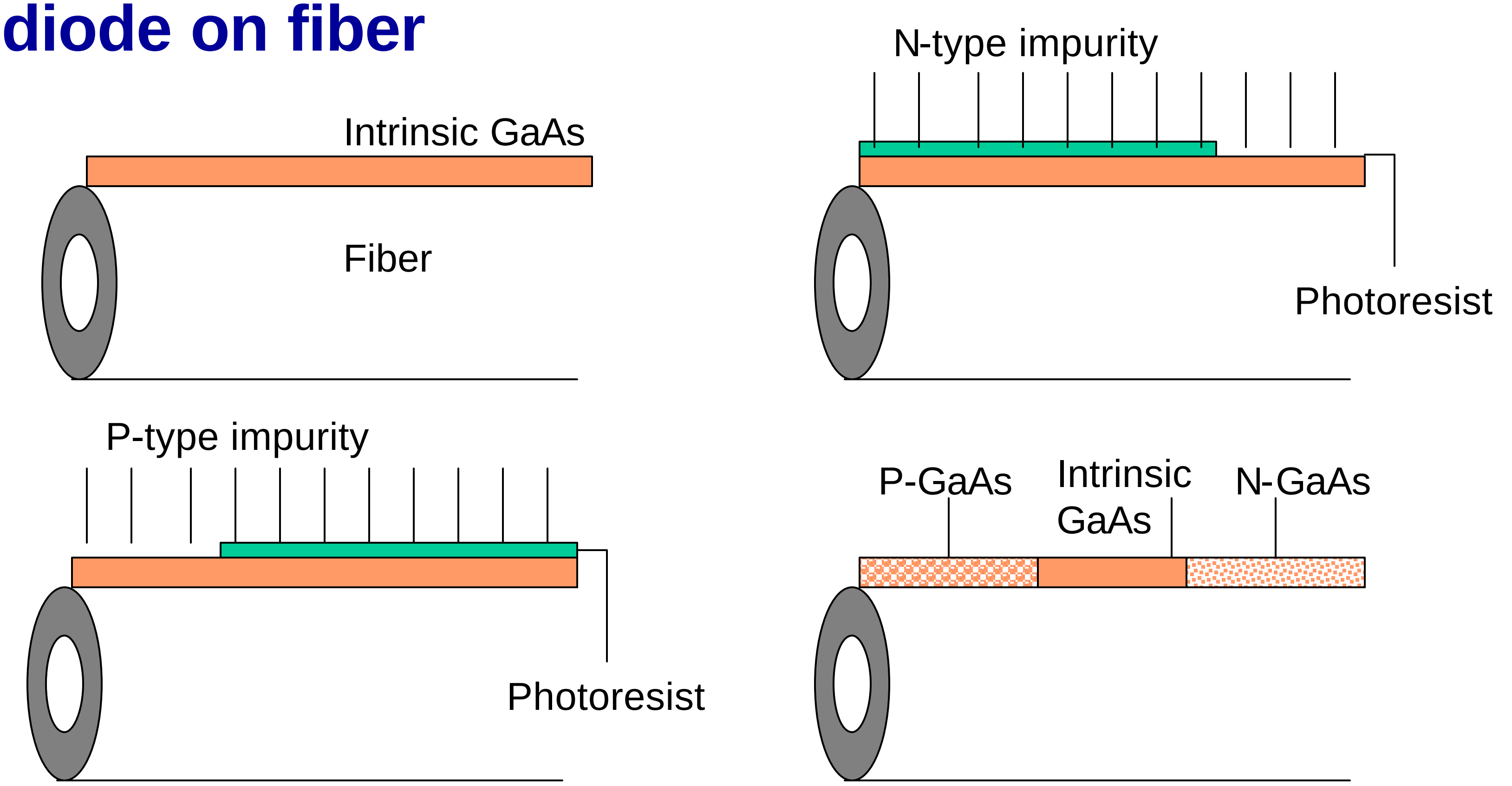


Sensors embedded within preform continuously generating and transmitting data

- 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