The MINOTAUR Project

**Micro and NanO Technologies for Automotive Research**

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Reason for the MINOTAUR Project

The New Paradigm for Automotive Sensors

- Phase 1 Automotive Sensors (completed)
  New Sensors for Enhanced Driver Information
- Phase 2 Automotive Sensors (completed)
  Sensor Communication with Control Computers
- Phase 3 Automotive Sensors (entering)
  Software Programmable Automotive Experience
Reason for the MINOTAUR Project

New Requirements for Automotive Sensors

- **Reduced Cost & Ease of Manufacture**
  - Introduction of Micro and Nano Technologies

- **Higher Performance**
  - Enhanced Sensitivity and Bandwidth

- **Greater Robustness**
  - Thermal, Shock and Chemical Resistance

- **New Sensor Modes**
  - Direct Measurement of Data
  - Reduced Use of Computer Models to Guess
Review of Existing Sensors

Existing Sensors Do Not Directly Measure Engineering Phenomena

- Cylinder Pressure
- Combustion Temperature
- Combustion Flame Speed
- Engine Output Torque
- Wheel Forces on Chassis
- Road Forces on Wheels
- Suspension Forces and Torques
Review of Existing Sensors

Bosch Sensors for Automotive Applications

- Drive train sensors:
  - Pressure sensor
  - Manifold absolute pressure sensor
  - Knock sensor
  - Intake air pressure sensor
  - Oxygen sensor
  - Throttle position sensor
  - Key sensor
  - Fuel sensor
  - Pedal position sensor
  - Speed sensor
  - Engine position sensor

- Safety sensors:
  - Airbag sensor
  - Tilt sensor
  - Tire pressure sensor
  - Pedestrian detection sensor

- Convenience features:
  - Air quality sensor
  - Immobilizer sensor
  - Lighting control sensor

- Other sensors:
  - Rain sensor
  - Ultrasonic distance sensor
  - Pressure sensor
  - Level sensor
  - Temperature sensor
  - Acceleration sensor

BOSCH Sensoren
Advanced Safety Vehicle (ASV)
Direct Measurement of Forces

1. MEMS Sensor on Wheel Communicates via RF to Transceiver on Chassis
2. MEMS Sensor on Shock Tower Measures Vertical Forces On Chassis for DSC Application
MINOTAUR Research Projects

Projects Overview

- MEMS Strain Sensors
- MEMS REPS Smart Plate
- SiC TAPS Sensors for Harsh Environments
- Integration of NEMS and MEMS by Localized Growth of Nanowires
- Nanowire Array Gas Sensors
MEMS Strain Sensors

Example: Auto Bearing
- Roller / Race interaction creates strain field ~100 μm wide
- This field dictates fatigue life of the bearing and relates directly to the force on the bearing, allowing for improvements in traction control applications.
- Require 0.1με resolution at 10kHz bandwidth

Foil gauges are limited in application and size:
- Sensitivity limits length to ~1.5 mm
- Require complicated & time consuming bonding

MEMS gauges offer solution:
- Inherently small
- Can incorporate bonding structures into device
- Integration with control, and data analysis CMOS also a possibility.
Sensor Resolution Vs. Bandwidth

![Graph showing the relationship between bandwidth and sensor resolution.](image)

**Measured Strain Sensitivity**

- Measured: 39 Hz/με
- Calculated: 36 Hz/με

*On-chip Strain Actuator*
Induction bonding is a fast, clean, and inexpensive heating process.

Generating an alternating magnetic field induces eddy currents in the metal.

Eddy currents cause localized heat generation from Joule heating.

Heat profile can be analyzed and controlled to prevent damage to the heat treatment of the steel.
Silicon-to-Steel IR Bonding

- Pb/Sn layer is then reflowed using infrared heating.
- Silicon test structures with Ti/Cu layer are cleaned.
- Test specimen are then exposed to infrared heating for a short period of time (30-60 seconds).
- The result: silicon bonded to steel!
Silicon Carbide TAPS Sensors

- Extreme Environment Sensor
  - 600 °C temperature, 300 atm pressure, 150,000 g shock

- Layers of 3 Different Silicon Carbide Materials

  - P3: Amorphous SiC,
  - P2: Poly 3C-SiC, (SiC MEMS structures)
  - P1: Epitaxial 6H-SiC, (SiC Electronics)
  - 6H-SiC Substrate
SiC High-Resolution Strain Gauge

- Works at high temperature > 600 °C Inherently small
- Can incorporate bonding structures into device
- Integration capability with control logic system
- Less susceptibility to fatigue due high fracture toughness of SiC
- Nano strain resolution in 100 Hz bandwidth at 600 °C

SiC Diaphragm Pressure Sensor

- Works at high temperature applications (600°C) in oxidative environments
- Si based MEMS pressure sensors fails in harsh conditions (>150 °C, oxidation environments, and very high pressure conditions).
- Deposition vs. Etching: precise control of diaphragm thickness through deposition gives high resolution
- 1% resolution at baseline of 300 atm up to 600 °C.
SiC Accelerometer

- High material toughness, high band gap, and oxidation resistance.

- Silicon-based accelerometers do not work in high-g, high electromagnetic radiation, and high temperatures (>150°C).

- Successful operation even above 150,000 g’s

- 1g resolution at 600 °C

SiC High-G Accelerometer

- Material compatibility.

- Monolithic integration with other sensors and logic circuits due to process compatibility whereas commercial sensors can not be integrated with this chip technology
MEMS REPS Smart Plate

100-250 Watts

- High Specific Power Generation
- Advanced Auxiliary
- Flexible Fuel Delivery
- MEMS Smart Plate
- Signature Control
- Combustion Stability & Characterization

100-250 Watts
Engine Performance Monitoring & Control Sensors

- Oxygen Sensor
- Knock Sensor
- Fuel Valve
- Fuel Delivery
- Pressure Sensors
- Temperature Sensors
- Silicon Carbide Wear Plate
- Crank Shaft Angle Sensor
- Fuel Delivery
MEMS Enabled Portable Power

Low cost manufacturing + Low unit cost MEMS $\Rightarrow$ High functionality, performance

- 17-4 Stainless Steel
- Silicon
- Magnetic Flywheel
- Electrical Power
- Shaft Work
- Low Cost Production
  - Low Part Count
  - Traditional Materials
- MEMS System Integration
Nanowire Array Gas Sensors

Background

Fabrication

Electrodeposition of metal in alumina nano-template

Advantages of Design

- High surface area to volume ratio
- High sensitivity
- Fast response time
- Lower power requirement than conventional sensors

Integration of NEMS and MEMS
Localized Growth of Nanowires

England, L.Lin UC Berkeley

- Microscale structures serve as the platform for silicon nanowire synthesis \(\Rightarrow\) resistive heaters/microbridges
- Heat is provided locally rather than globally
- Single crystal silicon & polysilicon structures serve as platforms
- Wirebond individual microbridges to a chip carrier
- Place chip carrier in a converted PECVD vacuum chamber
- MEMS bridges are positioned in close proximity to each other
- The growth bridge is resistively heated to reach the synthesis temperature
- The cold bridge serves to create local electric field to assist in SiNW orientation
- SiNW growth ends once contact with cold bridge takes place
Nanowire Array Gas Sensors

Oxygen & Hydrogen Sensors

**Oxygen Sensor**

- Metal oxide material reacts to oxidizing and reducing gases
  - \( \frac{1}{2}O_2 + e^- \rightarrow O^- \)
  - \( CO + O^- \rightarrow CO_2 + e^- \)

- The small diameter of nanowires allows the surface chemistry to alter the bulk conductivity of the wires.

- **Oxygen Ambient**
  - Depletion

- **Reducing Gas**
  - \( e^- \)

**Hydrogen Sensor**

- **PdNi Nanowires**

- **Anode**

- **Cathode**

- **H₂ Molecules**

- **Change in resistance of the sensing element in the presence of hydrogen molecules.**

- **Metal-Oxide Nanowires**

- **Schematic of the principle of operation**

- **R**

- **R*
The MINOTAUR Project

CONCLUSIONS

- New Micro and Nano Sensors
  - New Manufacturing Methods
- Enhanced Sensitivity and Bandwidth
  - Increased Performance for Closed-Loop Control
- Thermal, Shock and Chemical Resistance
  - Improved Sensor Robustness and Lifetime
- Direct Sensor Measurement of Data
  - New Modes of Vehicle Control and Programmability