Design and fabrication of a GaAs/Al$_{0.4}$Ga$_{0.6}$As micro-accelerometer based on piezoresistive effect

Guowen Liu$^{1,2}$, Binzhen Zhang$^{1,2}$ and Kairui Zhang$^{1,2}$

$^1$National Key Laboratory for Electronic Measurement Technology, North University of China Taiyuan, Shanxi, 030051, P.R.China
$^2$Key Lab on Instrumentation Science & Dynamic Measurement of the Ministry Education, North University of China, Taiyuan 030051, P.R.China

E-mail: jacky.mucklow@iop.org

Abstract. In this paper, a novel piezoresistive accelerometer based on the piezoresistive effect of GaAs/Al$_{0.4}$Ga$_{0.6}$As thin films was designed. The piezoresistive accelerometer contains four suspended flexural beams and a central proof mass configuration. The piezoresistive effect of a piezoresistor or thin film was used to make a resistor changing the output that is proportional to applied acceleration. The GaAs-based piezoresistive accelerometer was prepared with advanced surface micromachining processes, and bulk micromachining processes. Finally, the static pressure experiments were conducted on the sensing element. The experimental results showed that the combined semiconductor heterostructures and mechanical cantilevers have a good stress sensitive characteristic. The integration of these technologies promises to bring about a revolution in the applications of the semiconductor fine-structure devices.

1. Introduction
Although, the Si piezoresistor accelerometers have a good performance in practice, the temperature effect is very vital to it, the measurement result will shift with the variety of temperature. However, the GaAs material can make up the limitation of Si. Epitaxially grown III–V materials are widely used for the production of high-speed VLSI circuits, monolithic microwave integrated circuits, and laser based optical communication systems. More recently, there have also been growing interests in III–V materials for the fabrication of MEMS devices. For example, III–V surface micromachining has been demonstrated for applications including wavelength division multiplexing [1], optical telecommunication [2], and far infra-red photodetection [3], and GaAs has been widely used for the fabrication of MEMS components such as thermoconvertors [4-5], infrared detectors [6], and mechanical sensors [7]. MEMS based accelerometer is one of the most important types of the mechanical sensors, since there have been large demands for accelerometers in automotive applications, where they are used for crash detection, and for vehicle stability systems. In addition, due to small size and light weight, they are also used in biomedical and robotics applications for active motion monitoring, and in consumer for stabilization of pictures in camera, head-mounted displays.

Piezoresistive accelerometers have simplicity of the structure and batch-fabrication process, as well as a dc response, simple readout circuits, ability to meet the requirement of high reliability and low cost in addition to the potential for mass production [8-11]. But, the sensitivity of piezoresistive accelerometers is not as high as that of the capacitive and tunneling accelerometers. But these
problems can be improved by using novel materials. In contrast with Si, III–V compounds offer a number of material-related and technology advantages. There are some physical intrinsic properties of the direct band gap, low thermal conductivity, piezoelectricity effect, and its high saturation velocity of electrons [12-14].

In this study, a novel micromachined piezoresistive accelerometer based on the piezoresistive effect of GaAs/Al0.4Ga0.6As thin films is designed. And the accelerometer is fabricated using the lithography, wet etching, ion implantation and evaporated metal liftoff pattering technique. At last, Static pressure experiments on piezoresistor have been conducted. It is desirable that the application of ingenious materials of the sensor may improve the sensitivity.

2. Design of the accelerometer

We designed a piezoresistive microaccelerometer configuration with four suspended symmetric beams and a seismic mass based on the GaAs/Al0.4Ga0.6As. The piezoresistive thin films on each flexure beam is patterned into a transducer element, thus four piezoresistive transducers are arranged on the four beams symmetrically to form the sensing devices in the structures. Thin films are formed by airbridge technique at suitable places on the surface of the GaAs sensing beam, which themselves are fixed to the rigid frame at the ends as Figure 1. When an external acceleration is applied to the accelerometer, the seismic block will be displaced due to the inertial force. This movement of the seismic mass makes the beams deformed. As a result, the resistance of GaAs/Al0.4Ga0.6As piezoresistors will be changed. When there is incentive direct current, the change of resistance will be converted to an output voltage change by an external circuit. So we can get the external pressure by measuring the shift of current-voltage characteristics.

![Fig 1. Illustration of the top view of the GaAs piezoresistor accelerometer](image)

3. Fabrication of the accelerometer

After the GaAs/Al0.4Ga0.6As thin films are grown, piezoresistor microstructures are fabricated, using the lithography, wet etching, ion implantation and evaporated metal liftoff pattering technique. In step 1, the inductively coupled plasma (ICP) is introduced to etch two slots down to the piezoresistive layer, And Ti/Pt/Au metal is deposited and patterned on the top of the piezoresistive thin films mesas to form the ohmic contacts. In step 2, Using ICP etching forms the piezoresistor. In step 3, the ion implantation mask defines the area to be isolated, and the implantation of B+ with a dose of 2×10^{17} cm^{-2} produces an isolated layer among the piezoresistive device. In step 4, a 1240 Å PECVD Si3N4 film is deposited at low temperature (200°C) to form the insulating layer, then the Si3N4 film is etched by reactive ion etching (RIE) and the collector contact layer is exposed. In step 5, the polyimide sacrifice layer is coated and etched to fabricate air-bridge; down-lead holes are etched in the C and E electrodes, and a Ti/Au alloy metal is vaporized and etched.
to form the deck of the air-bridge. In step 6, Au/Ge/Ni metal is deposited on the deck to strength the contact layers and air-bridge, and then alloyed at 410 °C to form the electrodes. In step 7, the emitter electrode and collector electrode are fabricated through the metal layer by a shallow etch, using wet etching. In step 8, the sacrifice layer is wiped off and the double air-bridge structure of piezoresistive structure is formed as Figure 2.

Figure 3 describes the fabricating steps of the cantilever proof mass structure. The control hole etching technology is introduced to control the thickness of the beams accuracy. The three dimensional patterns of four independent thin GaAs cantilever beams are defined by a double side aligned selective of GaAs material through the opening in the masks to the membrane. After thinning the substrate down to 130 um by mechanically rubbing, the photolithography is used for masking the chip of the frontside of the membrane, and then 20 um cantilever beams are defined and etched initially from the front side by deep frontside vertical etching. Next, the cantilever beams and proof mass are formed successfully by etching 110 um from the backside of membrane again, when the frontside holes are visible. To make the sensing elements get a much lager stress signal, the sensing elements of piezoresistor are placed at the edge of the support rim and proof-mass where the stress variation is maximum.

4. Experimental and discussion

To study the piezoresistive effect of uniaxial pressure on sensitive element, the static pressure experiments have been conducted on Piezoresistor. The static pressure measuring system is shown in Figure 4. In this experiment, the Raman spectrum system was introduced as the quantitative analysis of the external pressure. The piezoresistor sensing element is fixed on the probe station and lighted by Raman laser. When compressive uniaxial pressures are applied to the sensing element along [110] direction using probes, the strain of the piezoresistor can be reflected by the Raman dispersion spectrum. So the Raman shifts acquire new values when the resistance is subjected to external mechanical stresses. The change in the Raman shifts can be calculated as [15]:

$$\Delta \omega_j = \omega_j - \omega_0 \approx \frac{\lambda_j}{2\sigma_0} \quad j = 1,2,3$$

(1)
Fig 4. The schematic diagram of the pressure experiment.

Where, \( \lambda_j \) (j = 1, 2, 3) are the eigenvalues of the matrix shown in (2).

\[
\varphi_{ij} = \begin{bmatrix}
p \varepsilon_{11} + q (\varepsilon_{22} + \varepsilon_{33}) & 2r \varepsilon_{12} & 2r \varepsilon_{13} \\
2r \varepsilon_{12} & p \varepsilon_{22} + q (\varepsilon_{33} + \varepsilon_{11}) & 2r \varepsilon_{23} \\
2r \varepsilon_{13} & 2r \varepsilon_{23} & p \varepsilon_{33} + q (\varepsilon_{11} + \varepsilon_{22})
\end{bmatrix}
\]

(2)

The following stress (\( \sigma_{xx} \)) and strain (\( \varepsilon_{ij} \)) tensors of the crystal coordinate system is resulted from a simple coordinate transformation [16].

\[
\varepsilon_{ij} = \begin{bmatrix}
\frac{(s_{11} + s_{12})}{2} \sigma_{xx} & \frac{s_{44}}{2} \sigma_{xx} & 0 \\
\frac{s_{44}}{2} \sigma_{xx} & \frac{(s_{11} + s_{12})}{2} \sigma_{xx} & 0 \\
0 & 0 & s_{12} \sigma_{xx}
\end{bmatrix}
\]

(3)

Here, \( s_{11}, s_{12} \) and \( s_{44} \) are elements of the compliance tensor of crystal. The \( p, q \) and \( r \) are the phonon deformation potentials and \( C_{ij} \) are elements of the strain tensor referred to the crystal coordinate system. From (1), (2), (3) and the basic physical quantities of GaAs, we can obtain:

\[
\sigma = -576 \Delta \sigma
\]

(4)

Where, “+” means the stress is a compression one, and “−” means the stress is a tensile stress. \( \Delta \sigma \) is the Raman shift, and \( \sigma \) is the external pressure. Corresponding to the Raman shift, it is a uniquely determined value of the local uniaxial stress in the GaAs piezoresistor. At the same time, the current–voltage (I–V) characteristics are tested by using Agilent 4156C semiconductor characteristic analyzer. The measured I–V curves of piezoresistor at room temperature are presented in Figure 5, and the resistance obtained by linear fitting in Origin 7.0. The shift of resistance under different pressures is shown in Figure 6. The resistance linearly increases with the strengthening of pressure.
Fig 5. Pressure dependent $I-V$ characteristics.

Fig 6. Resistance change under different pressure.

5. Conclusions
A micromachined piezoresistive accelerometer with a high sensitivity is designed. The technology for the fabrication of the piezoresistive accelerometer based on GaAs/Al$_{0.4}$Ga$_{0.6}$As thin films has been presented. The static pressure experiments show that the GaAs exhibits an excellent piezoresistive response, which may benefit to the future integration of the microsensors and the actuators.

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