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Micromachined ZnO Piezoelectric Pressure Sensor and Pyroelectric Infrared Detector in GaAs

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Abstract

Piezoelectric pressure sensors and pyroelectric infrared detectors based on ZnO thin film have been integrated with GaAs metal-semiconductor field effect transistor (MESFET) amplifiers. Surface micromachining techniques have been applied in a GaAs MESFET process to form both microsensors and electronic circuits. The on-chip integration of microsensors such as pressure sensors and infrared detectors with GaAs integrated circuits is attractive because of the higher operating temperature up to 200 oC for GaAs devices compared to 125 oC for silicon devices and radiation hardness for infrared imaging applications. The micorsensors incorporate a 1 μm-thick sputtered ZnO capacitor supported by a 2 μm-thick aluminum membrane formed on a semi-insulating GaAs substrate. The piezoelectric pressure sensor of an area 80 × 80 μm2 designed for use as a miniature microphone exhibits 2.99 μV/ μbar sensitivity at 400 Hz. The voltage responsivity and the detectivity of a single infrared detector of an area 80 × 80 μm2 is 700 V/W and 6 × 108 cm · √Hz/W at 10 Hz respectively, and the time constant of the sensor with the amplifying circuit is 53 ms. Circuits using 4 μm-gate GaAs MESFETs are fabricated in planar, direct ion-implanted process. The measured transconductance of a 4 μm - gate GaAs MESFET is 25.6 mS/mm and 12.4 mS/mm at 27 oC and 200 oC, respectively. A differential amplifier whose voltage gain is 33.7 dB using 4 μm gate GaAs MESFETs is fabricated for high selectivity to the physical variable being sensed.

I. Introduction

The ability to integrate microsensors together with electronic devices offers improved signal to noise ratio and small size. In contrast to the bulk fabricated sensors of the past, surface-machined microsensors are small and capable of being produced economically and reproduced in quantity due to integrated circuit technology. Integration of microsensors and transistors on the same semiconductor silicon chip is desirable for high system performance and potential low cost. This topic has been reviewed focusing on the new applications and challenges of integrating silicon sensors and signal processing circuits.[1]-[3] Silicon micromachining has been used to fabricate microstructures by anisotropic etching of silicon[4] and polysilicon deposition.[5] Recent advances in the microfabrication technology of silicon-based microsensors suggest possible approaches for GaAs-based processing. One approach to Gallium Arsenide (GaAs) micromachining involves the anisotropic etching of GaAs, with $Al_xGa_{1-x}As$ as an effective etch stop.[6] The on-chip integration of microsensors such as pressure sensors and infrared detectors with GaAs integrated circuits is attractive because of the higher operating temperatures of GaAs devices compared to silicon devices, the possibility of higher levels of monolithic system functionality through the on-chip integration of optical components such as lasers and detectors, radiation hardness of GaAs, and the possibility of higher circuit performance due to the higher mobility of electrons in GaAs than in Si. Specifically, commercial and military Silicon devices operate up to 75 °C and 125 °C due to its mobility degradation. But GaAs devices operate up to 200 °C, giving circuit designers more flexibility for the operating temperature range. GaAs devices also show hardness against alpha particles, which enables infrared image detection, an area for the application of infrared radiation detectors.

This paper describes the compatible integration of planar-processed microsensor structures using surface-micromachining technology with GaAs metal-semiconductor

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field effect transistor (MESFET) amplifiers. Relatively simple low noise differential amplifiers have been integrated with piezoelectric pressure sensors and pyroelectric infrared detectors. An important design issue in this work is the fabrication constraint of forming both amplifiers and deformable microsensor structures on a common GaAs semi-insulating substrate. Circuits using 4 μm-gate MESFETs are formed in a planar ion-implantation process. A deformable aluminum membrane implements both the pressure sensor and the infrared detector that use piezoelectricity and pyroelectricity of zinc oxide (ZnO) thin films. Integrated circuit processing is performed before the on-chip microsensor fabrication because of the fragile nature of microstructures. Low temperature microsensor processing steps are carried out to avoid degradation in MESFET device performance.

II. Fabrication Process

The compatible integration of ZnO-based microsensors with high performance GaAs MESFET amplifiers represents new challenges in photolithography, chemical etching, device parameter control, and limiting of process temperature. Detailed process steps can be found elsewhere.[7] As a sensor material, GaAs has several disadvantages that limit the use of GaAs for transducer applications. The most severe disadvantages are its low mechanical strength and low temperature processing constraint. Due to the relatively fragile nature of the deformable microstructures used for sensors, circuit fabrication took place before microsensor processing. Fabrication of micromechanical devices on GaAs is limited by these two factors. The structure of the integrated microsensor is shown in Fig. 1 and the process integration sequence is shown in Fig. 2.

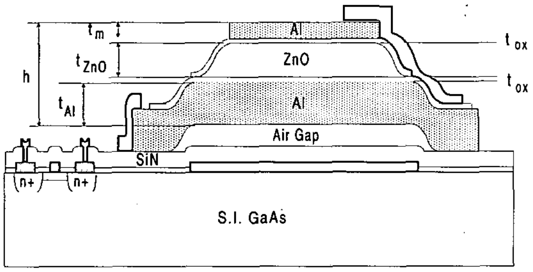

Fig. 1. The structure of an integrated microsensor

Semi-insulating GaAs wafers with 300 W · cm of resistivity, [100] orientation, and 19 mills of thickness were used in this work. Initially 500 Å of PECVD SiN_X was deposited on two wafers to protect the front surface. These wafers were selectively ion-implanted to form the channel, source, and drain. Implantation type, dose, energy and angle were determined to achieve 3×10^{17} cm^{-3} peak doping concentration with a 0.2 μm channel depth. The wafers were again selectively ion-implanted in the source and the drain. Implanted ions ($_{28}Si^{+}$) need to be electrically active before metallization. However, arsenic atoms tend to evaporate from the wafer at typical annealing temperatures of 800~900 °C. The dummy GaAs wafer placed on the device wafer keeps the arsenic pressure constant, thus maintaining the surface concentration of arsenic. The best rapid thermal annealing result was obtained at 900 °C in a "Heat Pulse" (AG Associates) incoherent lamp furnace in flowing argon ambient. SiN_X was etched before annealing and the wafers were placed on a 4" silicon wafer to which a thermocouple was attached to monitor the temperature. Source and drain metallization was done by evaporating Ni/Ge/Au using electron beam evaporator. Evaporated metal layers were annealed at 410 °C in the rapid thermal annealing system. The gate was recessed by 600 Å by wet etching to get a positive threshold voltage. Successive Ti/Pt/Au metal layers were evaporated and patterned by lift-off. The recessed gate provides low parasitic capacitances, shallow channel, and high gain. Platinum was used as an intermediate layer between titanium and gold to prevent diffusion of gold into the surface of the gate during later processing steps done at temperatures over 250 °C. Processing temperature over 250 °C lead to degradation of the Schottky barrier and the ohmic contact needed for satisfactory circuit performance. In particular, degradation of the Schottky gate leads to a reduction in circuit input impedance. 2000 Å of PECVD SiN_x was deposited for MESFET passivation during the sensor process. This completed the MESFET process.

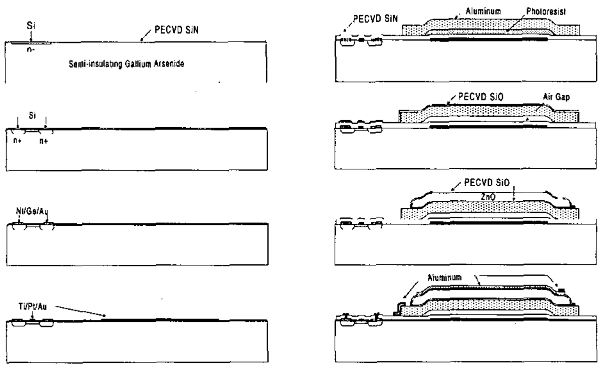

Fig. 2. Process sequence of an integrated microsensor

The most commonly used materials for surface micromachining in a silicon process are polysilicon and phosphosilicate glass (PSG) due to their mechanical strength and compatibility. However high temperature deposition and annealing of polysilicon and PSG make these materials incompatible with a GaAs process. An alternative approach is to use aluminum as a support material and photoresist as a sacrificial layer. The sensor process began by spinning sacrificial photoresist that would be removed to leave an air gap later in the process. A photoresist (KTI-825) designed to be stable at high temperature was baked at 140 °C. This hardened the photoresist to further development when the area of metal membrane was developed for lift-off. 2 μm-thick aluminum film was evaporated and lifted-off to form a supporting structure on which the active ZnO was deposited. Lift-off of aluminum membrane was another challenge. Thick photoresist (3 μm) and chlorobenzene soaking have made the lift-off process possible. The photoresist was then removed in heated photoresist stripper to form an air gap. The aluminum membrane was deformable and served as a micromechanical component that reacted to the pressure. PECVD SiO_2 was deposited to prevent electrical leakage through the ZnO layer. The active ZnO thin film was deposited to a thickness of 1 μm by RF planar magnetron sputtering using a hot-pressed source target . The ZnO source target was doped with manganese to control the resistivity. A high electrical resistance is desirable in order to serve as a capacitive transducer element. For integrated sensor applications, it is desirable to grow ZnO thin film with the c-axis orientation perpendicular to the substrate. The film showed a high degree of c-axis orientation normal to the substrate when it was grown at 250 °C. In compatible processing of ZnO thin films with GaAs MESFETs, any steps that chemically etch ZnO must not attack electronic elements. The particular etchant which has been found most reliable is a solution of acetic acid : phosphoric acid : water (CH_3COOH : H_3O_4 : H_2O) in a volume ratio of 1:1:30. Another PECVD SiO_2 layer was deposited to encapsulate the ZnO layer. The top electrode was formed perpendicular to the ZnO layer by lift-off, contact openings were cut and metal interconnections were made. This completed the integrated sensor process.

III. Sensor Characteristics

The piezoelectric pressure sensor fabricated using surface-micromachining techniques for use as a miniature microphone has been tested. Since the pressure sensor is designed for use as a miniature microphone, the structure is not hermetically sealed but simply supported on the substrate in order to detect the incoming acoustic pressure as shown in Fig. 1. The simply supported aluminum membrane is capable of detecting the acoustic pressure at higher sensitivity than the hermetically sealed structure because it is supported on two sides and aluminum is more brittle than polysilicon. In addition the piezoelectric coefficient of ZnO is much higher than that of polysilicon leading to higher sensitivity than conventional pressure sensors[5]. The sensitivity of an piezoelectric pressure sensor was measured using a shielded speaker as an acoustic source, a sound level meter, and a Princeton Applied Research Model 5209 lock-in amplifier. The speaker is shielded to block the electromagnetic fields generated from the speaker. The electromagnetic fields strongly interfere with the measurement if precautions are not taken. The speaker and the shielded metal box that contains the bonded pressure sensor and the speaker are grounded. Acoustic absorbing materials are covered on each side of the box to minimize sound reflections. Measurement has been performed by varying amplitudes at audible frequencies, specifically at 400 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz. A sound level meter at five frequencies has calibrated the pressure generated by the sine waves of the speaker. The measured piezoelectric responses for 3 different devices at 4 kHz are shown in Fig. 3. The response increases almost linearly as the pressure increases. The slope of the plot indicates the sensitivity of the piezoelectric pressure sensor. The measured sensitivities are plotted in Fig. 4. The frequency response of the piezoelectric pressure sensor is shown in Fig. 5. The damping frequency of $20\times20\ \mu m^2$ and $80\times80\ \mu m^2$ devices are 6 kHz and 10 kHz respectively. It turned out that a $80\times80\ \mu m^2$ device is suitable to miniature microphone application for voice recording because it shows flat response in the frequency range of human voice (100 Hz ~ 3 kHz).

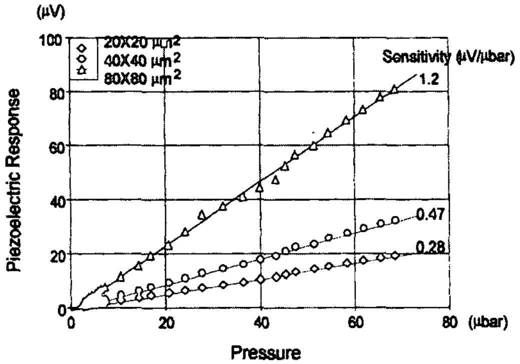

Fig. 3. Piezoelectric response versus pressure at 4 kHz

The same devices used as piezoelectric pressure sensors are characterized as pyroelectric infrared detectors because ZnO exhibits both the piezoelectric and pyroelectric effect. Pyroelectricity is the manifestation of the temperature dependence of the spontaneous polarization in solids. When radiation power is absorbed by the pyroelectric material, the temperature of the crystal changes. The change in crystal temperature alters its polarization and induces a change in the surface charge. The change in surface charge produces an electrical signal proportional to the incoming power. ZnO has a hexagonal wurtzite structure and a natural electric dipole moment in the absence of an electric field. An electric field is produced in ZnO capacitor when ZnO experiences temperature change. The air gap between the aluminum membrane and the GaAs wafer provides a low thermal mass and high thermal isolation from the substrate. The main advantages of the pyroelectric detector are the ability to measure electromagnetic radiation (especially infrared), small temperature changes of heat flux, and its high sensitivity at room temperature. The sensor structure is more advantageous than conventional single crystal or bulk ceramic ferroelectric capacitors because of a higher figure of merit due to its reduced thermal mass.[8] This reduced thermal mass is obtained by featuring an air gap which isolates the sensor from the substrate.

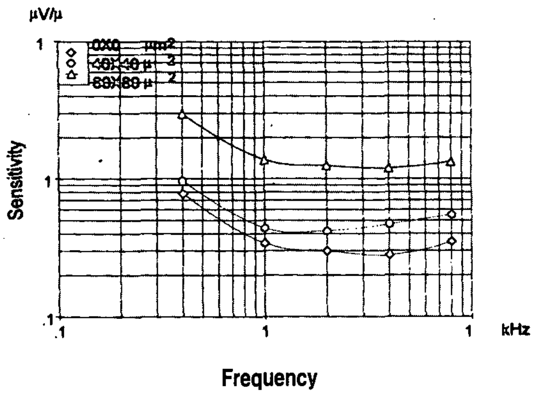

Fig. 4. Piezoelectric pressure sensitivities

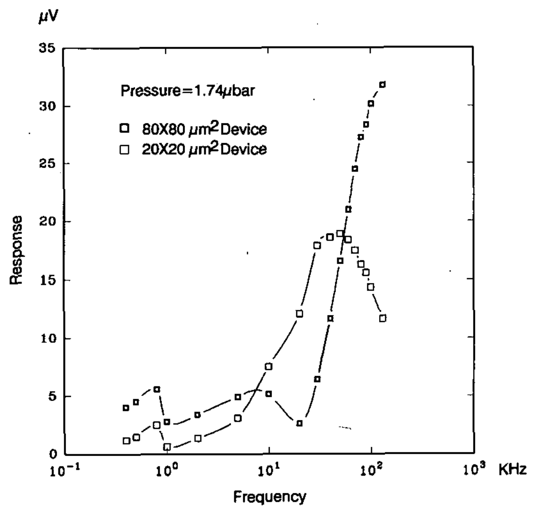

Fig. 5. Frequency response of a piezoelectric acoustic pressure sensor

The pyroelectric coefficient was measured by Polla[9] and found to be 1.4×10^{-9} C/cm^2 • °K. The pyroelectric infrared detector characterization was carried out using a blackbody radiation source, a light chopper and a lock-in amplifier. The chopping frequency dependence of the responsivity (R_V) and the specific detectivity (D*) is shown in Fig. 6. This figure indicates the composite detector time constant 53 ms compared to the calculated thermal time constant 12.5 msec of the 1 μm-thick ZnO thin film. This discrepancy is caused by decrease of the heat capacity at high frequencies and the measured value includes the time constant of the amplifying circuit. The performance of the practical pyroelectric detector is limited by the level of noise sources. The performance degrades from the ideal detector because of the transducer efficiency and the radiation noise sources related to the dielectric loss and the amplifier. The measured voltage responsivity and the detectivity of a single infrared detector of an area 80×80 μm^2 device is 700 V/W and 6×10^8 cm • $\sqrt{}$Hz/W at 10 Hz respectively. This remarkably high detectivity is attributed to the reduced thermal mass of the detector compared to the conventional bulk infrared detector[10].

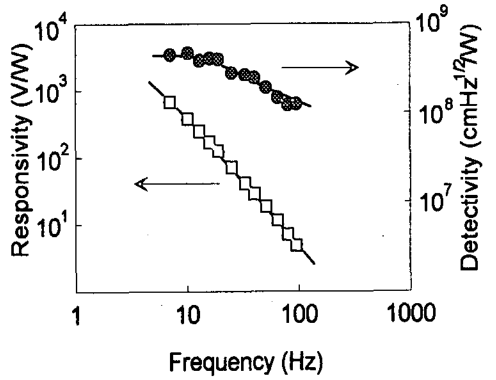

Fig. 6. Frequency dependence of responsivity Rv and detectivity D*.

IV. GaAs MESFET for Sensor Interface

GaAs MESFETs fabricated by ion-implantation process have been tested at room temperature. Fig. 7 shows the measured I_{DS} vs. V_{DS} curves for a 4×800 μm^2 (gate length × channel width) ion implanted, enhancement mode GaAs MESFET. The gate voltage is limited to 1 V to avoid excess gate current. Measured SPICE JFET model parameters are listed in Table 1. For application to piezoelectric and pyroelectric sensing schemes, the specific advantages offered by integrated GaAs circuits over silicon MOS or bipolar circuits include a wider operating temperature, increased hardness to radiation and high gain. The semi-insulating nature of the GaAs substrate allows circuit design to be done without considering the body effect. In practice, uniformity of processing results over the chip area is difficult to achieve with many of the common fabrication techniques and device crosstalk increases the device mismatching problem[11]. Ion implantation offers better uniformity of device characteristics over other fabrication technique [12]. For the piezoelectric and pyroelectric sensors of this work, coupling of the signal to the amplifier requires that the input circuit have a high input impedance and that the sensor have excellent signal charge retention. The enhancement mode GaAs MESFET provides much higher input impedance because of low doping density. This work is restricted to relatively simple circuits for piezoelectric and pyroelectric sensing using differential input schemes.

Table 1. SPICE JFET model parameters for a $4\times800\mu\ \mathrm{m}^2$ GaAs MESFET

Name	Parameter	Units	Measured
N_D	Channel Doping Density	cm^{-3}	6×10^{16}
V_T	Threshold Voltage	V	0.08
g_m	Transconductance	mA/V	20.5
β	Trans. Parameter	mA/V^2	16.8
λ	Channel Length Modulation	1/V	0.1
g_{ds}	Drain Conductance	μA/V	30.4
R_S	Source Resistance	W	47.1
R_G	Gate Resistance	W	87.65
R_{series}	Series Resistance	W	40
n	Ideality Factor	-	1.21

A differential sensing scheme using an active sensor and a reference sensor is shown in Fig. 8 where transistor channel length L is kept constant at 4μm This scheme compensates the low input impedance of the MESFET and allows to detect the potential difference between the active and the reference sensors. The gain of the amplifier is given by

$$A_v = -g_{m2}(r_{o1} \| r_{o2})$$

where the transistor transconductance g_m is 26.625 mS/mm and the output resistance r_o of a depletion mode MESFET is 2 kW · mm. A voltage gain of 33.7 dB is obtained for a differential amplifier in Fig. 8 and is limited by the product of the amplifier transistor transconductance and the lower of the two channel resistances. An increase in the transconductance can be achieved by increasing W/L ratio. However decreasing L leads to a loss of output resistance. Increasing W leads to an undesirable increase in chip area and device capacitance. The SEM photograph of an integrated microsensor is shown in Fig. 9.

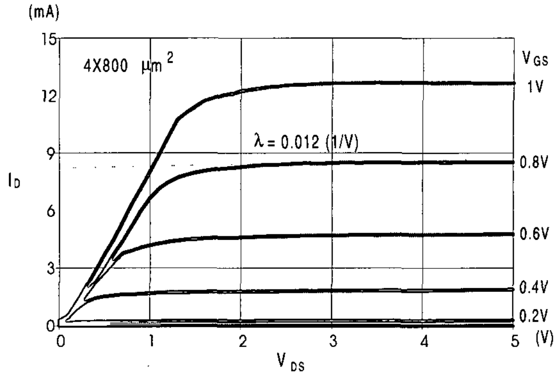

Fig. 7. Measured I-V characteristics for a $4\times800\mu\ \mathrm{m}^2$ ion-implanted, enhancement mode GaAs MESFET

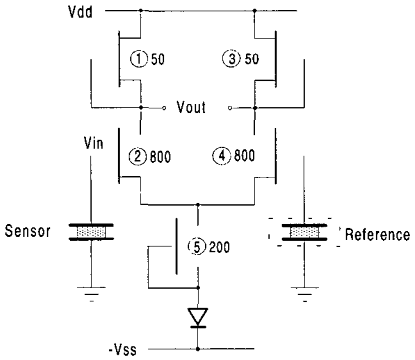

Fig. 8. GaAs MESFET differential amplifier

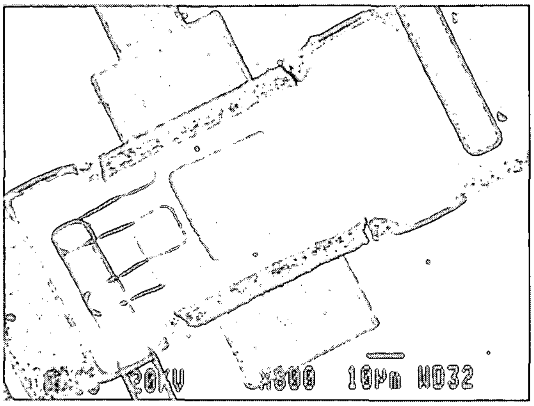

Fig. 9. SEM photograph

V. Conclusions

This work has demonstrated for the first time the ability to fabricate ZnO-based pressure sensors and infrared detectors together with MESFETs on a common GaAs chip. The on-chip integration of microsensors such as pressure sensors and infrared detectors with GaAs integrated circuits is attractive because of the higher operating temperature up to 200 °C for GaAs devices compared to 125 °C for silicon devices and radiation hardness for infrared imaging applications The pressure sensor is based on the piezoelectric effect, while the infrared detector is based on the pyroelectric effect in ZnO thin film. An 80×80 μm^2 piezoelectric pressure sensor showed 1.2~3 $\mu V/\mu bar$ sensitivities at 0.4~8 kHz audible frequency range. The voltage responsivity and the detectivity of a single infrared detector of an area 80×80 μm^2 is 700V/W and 6×10^8 cm $\cdot \sqrt{Hz}$/W at 10 Hz respectively, and the time constant of the sensor with the amplifying circuit is 53 ms. GaAs MESFETs have been fabricated in a compatible process with ZnO thin film deposition and patterning techniques. The measured transconductance of a 4 μm-gate GaAs MESFET is 25.6 mS/mm and 12.4 mS/mm at 27 °C and 200 °C, respectively. An ion implantation process has been used to provide better uniformity of MESFET characteristics. Gate metallization was made to be stable during sensor fabrication. Because of the low mechanical strength and the low process temperature of GaAs, silicon surface-micromachining technology cannot be as easily duplicated in GaAs. Instead the low temperature deposition of photoresist as a sacrificial material and the use of aluminum as a support material has been adopted. Although aluminum is not as strong as polysilicon, or Silicon nitride, the microstructures fabricated demonstrated enough mechanical strength to form useful physical microsensors.

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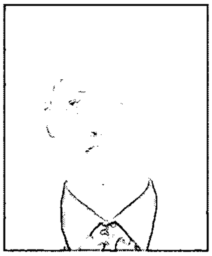

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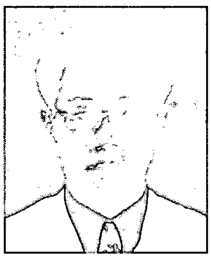

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