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Compound Semiconductor Microsensors for Applications in Mechanical Engineering

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ABSTRACT: The GaAs- and InP-based compound semiconductor technology enables the realization of intelligent sensor systems showing excellent and formerly not achievable performance. Bandgap engineering allows outstanding electrical properties including the use of quantum phenomena. In addition, these material systems offer a simplification of technology with a number of features for micromechanics, such as the etching selectivity. Various microelectromechanical systems or sensors can then be easily fabricated combining electronic and mechanical functions on the same chip. The mechanical functions include suspended bridges and membrane structures realized by front and back side processing.

INTRODUCTION:

Bulk or surface micromachined III-V sensors for application under critical surrounding conditions, such as operation at high temperatures, have been developed for mechanical engineering applications (pressure, gas flow, acceleration, position and infrared sensors). These different families of sensors will be described in detail within the following paragraphs. Concepts for a wireless transmission of supply energy and sensor signals (telemetry connection) have also been taken into account and investigated.

THERMOELECTRICAL MEMBRANE SENSORS:

Thermal sensors are applicable for the measurement of infrared radiation, mass-flow and flow direction as well as electrical power from DC up to sub-mm waves [1, 2, 3]. The advantages of GaAs and InP based sensors are the following: (i) high Seebeck coefficients which enable the integration of temperature sensing functions, (ii) high thermal resistivity of the compound semiconductors for optimum thermal isolation and (iii) easy micromachining of free standing and suspended heterostructures (Fig. 1). The combination of the membrane concept and these properties results in sensors of high thermal sensitivity (increase by factor >20). The sensors also show excellent linearity, dynamic range (>50dB), flat frequency response, low reflection coefficient and response time of only some milliseconds.

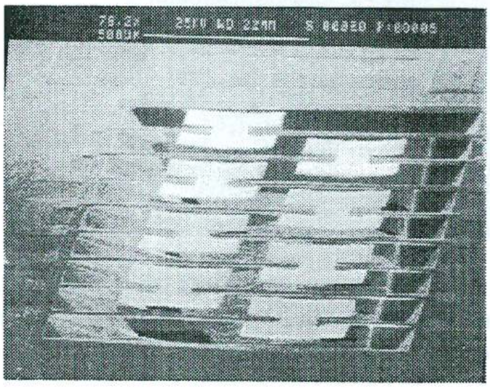

Fig. 1: Front side bulk micromachined IR-sensor based on InP with free standing InGaAs bridges and eight radiation absorbers. The absorbers consist of InGaAs thermocouples covered with gold-black. The relative detectivity is $7.1 \cdot 10^8$ cmHz $^{-1/2}$/W .

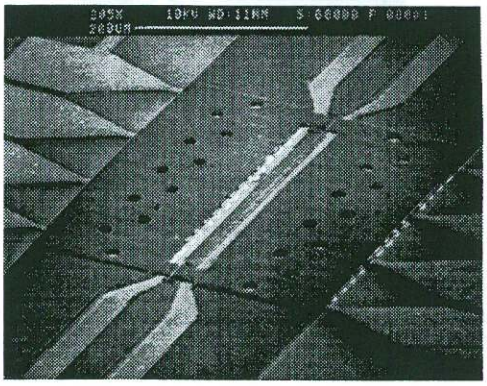

Fig. 2: Microwave power sensor employing coplanar waveguide and thermopile on a 1µm AlGaAs membrane with 3µm distance from the bulk material. The temperature independent resistivity of a NiCr film is used for the central conductors.

Microwave power sensors are fabricated in MESFET or MESFET-like technology. They employ the inherent lossy characteristics of on-wafer coplanar waveguides in order to measure the transmitted RF power from the temperature rise of the central conductor of the waveguide without any further attenuation of the RF signals. The sensors can be fabricated in terminating load configuration or as power throughput configuration. Therefore the waveguide is placed on a membrane structure in the vicinity of a thermopile as shown in Fig. 2. The response is independent of the waveform, hence the sensor is dedicated to average power measurements.

The thermopiles employ the high Seebeck coefficient of GaAs, resulting in a very good thermal sensitivity. The inherent linearity of this sensor concept, the high sensitivity of 2.02V/W and the flat frequency response can be seen in Fig. 3 and Fig. 4. The bandwidth of this coplanar sensor structure is above 26GHz and is only limited by the layout of the transmission line, not by the sensor principle itself.

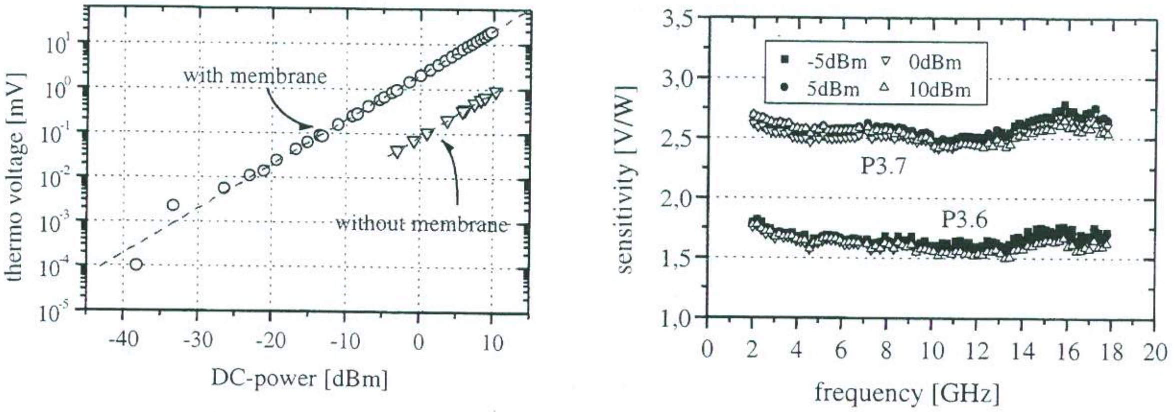

Fig. 3 and Fig. 4: Calibration of a power sensor in a 50Ω terminating load configuration. After the etching of the membrane, the sensitivity is increased by a factor of 20 because of improved thermal isolation of the sensor structure. Because of the low thermal capacitance of the membrane, the response time is also being strongly reduced.

Another advantage of these types of sensors is their direct compatibility with monolithic microwave integrated circuits (MMIC), for example for the measurement of output stage power, the realization of integrated network analyzers or miniature low reflection power meter probes.

A micromachined mass flow and flow direction sensor is shown in Fig. 5 and Fig. 6. Here a stripe-shaped NiCr heating resistor located on a 1µm membrane is thermally coupled with two thermopiles in a differential configuration. The heat from the heater stripe is being transferred to the thermopiles by the medium flowing along the planar surface. Therefore this concept shows not only a high sensitivity of flow rate, but also an excellent angle dependence as visible in Fig. 7.

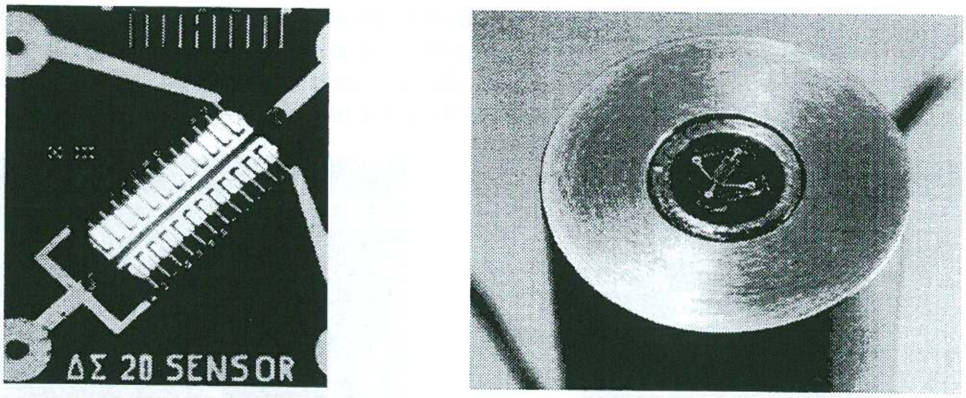

Fig. 5 and Fig. 6: Photograph of a GaAs gas flow sensor. The central NiCr heater stripe located on an AlGaAs membrane has a length of 800µm. Heater and thermopiles are connected to the back side of the chip through via holes. The complete sensor is packaged in a metal ring for planar installation in pumps and turbines.

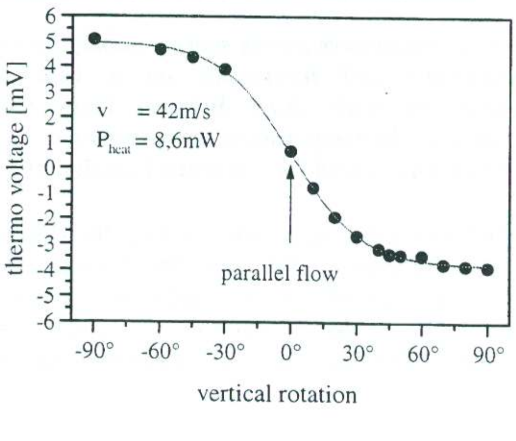

Fig. 7:
Calibration of the angle dependence of a gas flow sensor. The output voltage is the differential signal of the left and the right thermopile shown in Fig. 5. A perpendicular placement of two sensors enables the measurement of flow direction in an angle range between -180° and +180°.

The sensor type presented here can be used in compressors and turbines because of the planar concept with backside contacts. The temperature range exceeds 300°C with only very slight changes in sensitivity between 20°C and 250°C. Using the described membrane concept, thermally actuated Fabry-Perot filters for Wavelength Division Multiplex Systems (WDM) have also been realized [4].

FIELD EMITTER BASED SENSORS:

According to the Fowler-Nordheim theory, the field emission current depends exponentially on the distance between GaAs cathode and anode. Hence, this effect is predestined for vibration, acceleration and pressure sensing. We have designed and fabricated a lateral field emitter structure consisting of two wedges vis-a-vis. They are etched anisotropically in n^+-doped GaAs. One of the wedges is released by front side bulk micromachining to form a movable cantilever. This cantilever contains the seismic mass m of the accelerometer. Acceleration or vibration causes the cantilever to bend, which modulates the emission current due to the variation of the distance between the cathode and the anode.

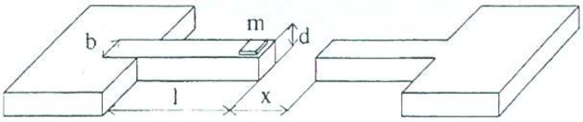

Fig 8: Concept for a lateral field emitter based acceleration sensor.

TECHNOLOGY OF MICROMACHINED LATERAL EMITTERS:

A cross-section of a micromachined lateral field emitter pair is shown in Fig. 9. This configuration can be used as vibration sensor with the left cantilever being sensitive to mechanical vibrations of high frequencies. The resonance frequency can be tuned by the geometry and the mass of the cantilever. In the case of an accelerometer an additional seismic mass can be placed on the same cantilever. The sensitive cantilever (left one) is deflected under mechanical actuation with respect to the right one which should be insensitive. This causes a modulation of the field emission current through the device. Both electrodes can be used as emitter.

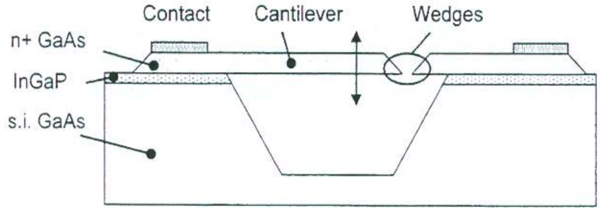

Fig. 9: Schematic cross-section of a lateral field emitter in cantilever configuration for vibration sensing.

For the fabrication of this device the following process steps have been used:

1. The 2µm thick n^+ GaAs layer has been anisotropically etched using citric etchant. This etchant stops at the 100nm thin InGaP layer, so that the cantilever thickness is precisely defined. The wedges are oriented such that the lower GaAs edge at the interface to the InGaP will form the emitter. This guaranties the required sharpness.
2. The ends of the mesas are contacted with AuGeNi ohmic contacts.
3. Windows are etched into the InGaP layer side by side to the wedges.
4. These windows serve as access holes for the anisotropic micromachining process. The bulk GaAs underneath the cantilevers is removed by anisotropic wet etching with phosphoric etchant.

In the final step, the remaining InGaP layer can be removed selectively against GaAs with $HCl:H_3PO_4$ without the need of lithography. In this step the sharp wedge is also released. The radius curvature of the wedge is smaller than 50nm, as shown in Fig. 10.

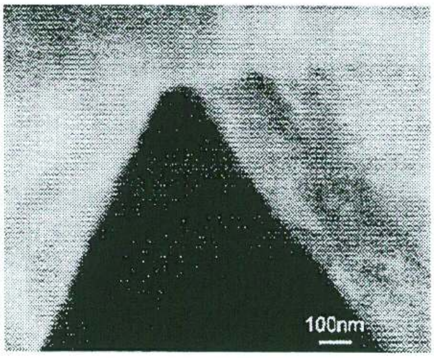

Fig. 10:

SEM picture of an anisotropically etched wedge.

HALL SENSORS AND TELEMETRY:

Using an AlGaAs/GaAs 2DEG structure, monolithically integrated 3D deformation sensors [5] have been fabricated. Supply current and power related magnetic sensitivities of the Hall crosses are $S_I = 699$ V/AT and $S_P = 139.7$ V/WT respectively. These devices are employed for the analysis of tire parameters in automotive engineering. The AlGaAs/GaAs material system offers a high electron mobility (about 7000 cm^2/Vs at 300K) suitable for high sensitivity and low-power sensor application for wireless measurement systems [6]. The position sensor employs four monolithically integrated Hall crosses and an additional temperature sensor. A photograph of the sensor chip is shown in Fig. 11.

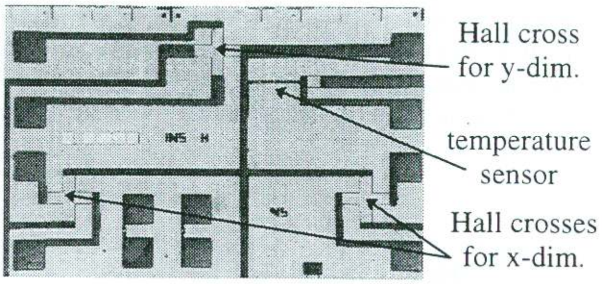

Fig. 11:
Section photograph of the position sensor.

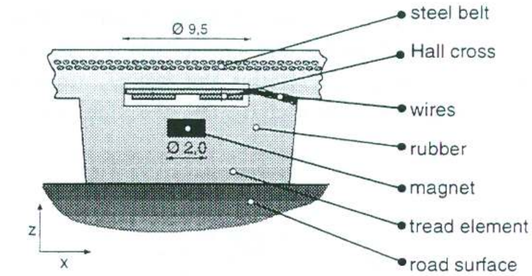

Fig. 12: Concept of the deformation sensor shown in a section of a tire.

The differential signals of two crosses in x- and y-direction deliver the x- and y-deformation output signal. The sum of the four Hall voltages forms the z-signal. A permanent magnet is mounted within the stub of the tire at a distance of 1mm from the sensor for deformation monitoring (Fig. 12). Due to the high electron mobility resulting in a very high sensitivity of the Hall crosses, a miniaturization of the permanent magnet and the complete sensor system is possible. The sensor chips are glued to thick film ceramic carriers and shedded within epoxy resin. The dimensions of the shedded module are d = 9.6mm and h = 2mm. The complete system of sensor and permanent magnet is then moulded into the tire rubber.

The sensor can be used for measurement of tire deformation in x-, y- and z- direction and these results can be employed for an early detection of local tire slip and other driving parameters. The sensor shows a very good linearity in x- and y-direction. The characteristics in z-direction are non-linear but they can be easily compensated. The signals shown in Fig. 13 are typical for the results of driving experiments.

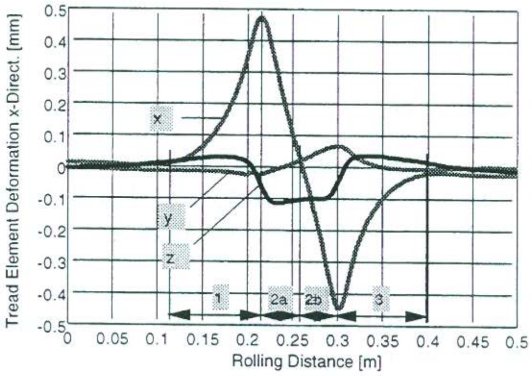

Fig. 13:

Basic signals on a flat base tire test bench.

1 - running in zone
2 - contact area
(a = braking, b = driving)
3 - running out zone

The y-signal is a measure of the deformation in lateral direction. A deflection can be seen although the tire runs without lateral force.

Test stand experiments have shown the potential to measure tire pressure (z, x), wheel load (z), force in circumferential (x) and lateral direction (y). The sensor also has a potential to estimate the actual use of friction between tire and road.

The sensor miniaturisation enables the placement of chip and magnet in a single tire tread element. So standard steel belt tires can be investigated without any distortion of the magnetic field caused by the steel cord (Fig. 12). The power consumption has been successfully reduced to enable the use of a transponder system.

For a wireless transmission of the sensor signals from inside the tire, a miniature low power four channel telemetry system has been realized. The sensor signals are used in multiplexed configuration in order to frequency modulate a 433MHz ISM (industrial, scientific and medical applications) carrier. A significant task related to this measurement system is the power supply of sensor and telemetry. The permanent supply of an active signal processing circuitry is problematic, as changes in construction of tire and rim should be avoided.

Therefore passive transponder concepts (Fig. 14) have been investigated for a completely stand-alone measurement system [7]. The Hall crosses were powered from the outside of the tire by two incident RF signals and generate a modulated output signal because of their non-linear characteristics:

$$U_H(t) = k \cdot I_0(t) \cdot B(t) \qquad (1)$$

Where $I_0(t)$ is the time function of the Hall sensor RF operating current and $B(t)$ is the time depending magnetic field strength which contains the position information.

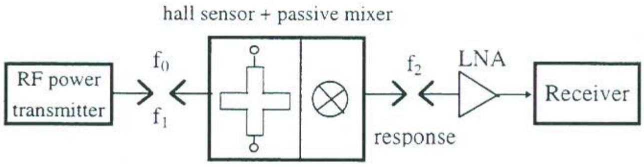

Fig. 14: The passive transponder concept.

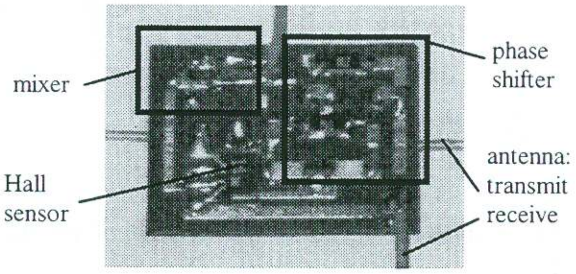

Fig. 15: Experimental realization of the passive transponder employing a GaAs Hall sensor.

RTD STRESS-SENSORS:

Resonant tunneling diodes (RTDs) are quantum electronic devices which exhibit a negative resistance region (NDR) in their I-V characteristics. With III-V-compounds, a compositional confinement is used to create energy well and barrier structures for the carriers. This gives rise to the existence of allowed quasi-discrete energy levels for electrons and holes as well as a non-zero probability of tunneling through higher energy barriers. For a double barrier structure, a resonant enhancement of the conductivity is observed if the energy of incoming electrons coincide with the level in the well. Different configurations of RTDs can be achieved using GaAs-, InP- or Antimonide-based III-V-material systems. RTD-pressure or -stress sensors are based on the change of the position of the energy states in the quantum well with applied external pressure. A shift is then obtained in the I-V characteristics, mainly in the NDR. This shift is asymmetric for AlGaAs/GaAs RTDs and symmetric for the InAs/AlSb/GaSb ones [8],[9]. This dependence offers remarkable advantages for the fabrication of miniaturized micromachined membrane pressure sensors (Fig. 16): (i) the RTD is a vertical device with lateral dimensions which can be drastically reduced (ii) the change in the current-voltage characteristics can be transformed in a frequency change of a relaxation oscillator including the RTD.

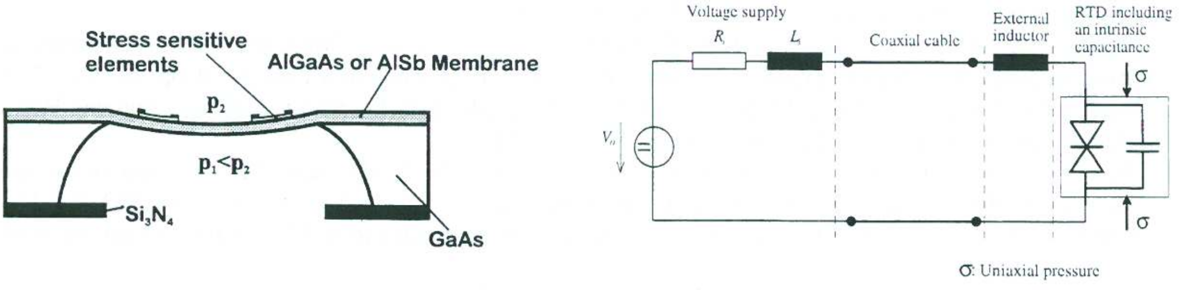

Fig. 16: III-V membrane concept for RTD-pressure sensor and the measurement set-up for a $Al_{0.6}Ga_{0.4}As/GaAs$ RTD-bulk sensor with frequency output.

The sensor sensitivity can be increased by using the different states of stress existing on a membrane structure. Measurements with $Al_{0.6}Ga_{0.4}As/GaAs$ RTDs on (001)-oriented GaAs wafer with [110] directed uniaxial pressure are shown in Fig. 17. A sensitivity of 100 mV/Kbar and a corresponding K-Factor of about 150 have been measured. The

K-Factor, which is the figure of merit for the characterization of pressure effects for sensor applications, is defined here as:

$$K = \frac{\Delta V_{peak}}{\varepsilon\, V_{peak}} \tag{2}$$

V_{peak} is the peak voltage of the I-V-Chararcteristics of the RTD and ε is the strain. The value reported here is comparable to those of Si-based resistive effects and three times higher than in GaAs-piezoresistors [10]. From the frequency-dependent measurement, sensitivities of up to 80 kHz/Kbar have been obtained. InAs/AlSb/GaSb RTDs have shown similar sensitivities with symmetrical shift in the I-V-characteristics.

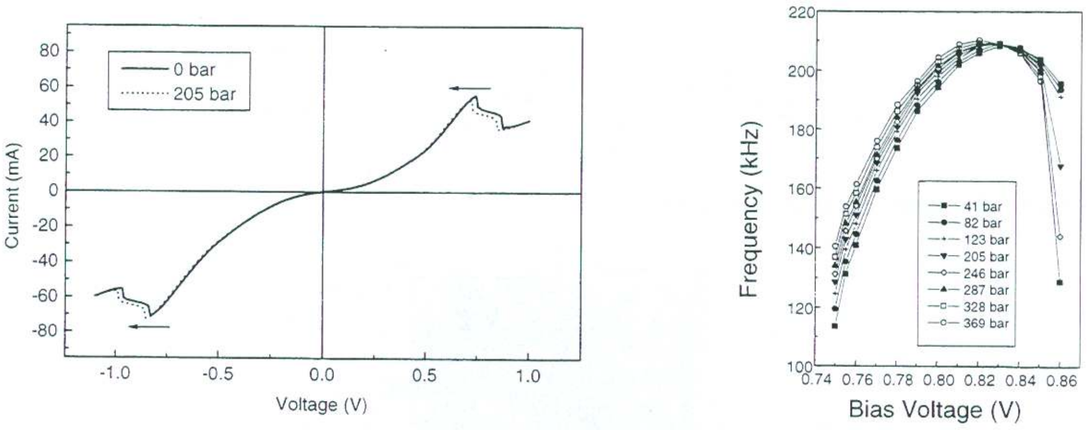

Fig. 17: Room temperature pressure dependent I-V characteristics of an $Al_{0.6}Ga_{0.4}As$/GaAs RTD and the corresponding frequency response.

CONCLUSION:

Various types of compound semiconductor sensors for an application in the field of mechanical engineering have been presented. The sensor concepts are investigated under the maxim of a practical application and not only in the context of fundamental research. Nevertheless, especially the field-emitter based acceleration sensors and the RTD-based stress sensors employ so far unused physical effects that show a large potential for future sensor applications and need further research efforts.

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