Innovative pressure and Hall sensors based on semiconductor compounds

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Abstract

The recent progress made in the crystal growth, epitaxial deposition and device processing technology of semiconductors has opened the way to the development of new categories of sensors with improved properties.

To satisfy the market requirements, semiconductor multilayer systems like SOI (Silicon On Insulators) or GaAs-based heterostructures are particularly attractive. Recently, a new class of the wide band gap semiconductor like SiC or the III-V nitride have been also considered for high power, high temperature and high frequency device applications.

We present new kinds of sensors based on different semiconductor compounds, available for two different applications : 1) pressure sensors for high temperature and high-pressure environment, 2) magnetic sensors for different applications.

1. Introduction

The intrinsic properties of new semiconductor compounds, matched with device miniaturisation techniques, open the way to innovative solutions when the classical concepts turn to be inefficient in a harsh environment or for small mass and volume for example.

In this paper, we present two examples of sensors based on semiconductors : Firstly, a high performance monolithic pressure sensor for high temperature (up to 200 °C) and high pressure (up to 2 kbar) operations. Secondly, a magnetic sensor with a high sensitivity, a very low thermal drift and excellent metrological performances. The performances of these sensors are directly linked to the high material quality, the excellent control of the band gap engineering and the control of the doping technique, particularly the dopant segregation achievable by MBE.

2. Pressure Sensors

Semiconductor pressure sensors are generally based on piezoresistivity, i.e. on the change of the electrical resistivity under application of uniaxial stress or hydrostatic pressure. The most common version uses gauges diffused or implanted into an Si substrate and operating in a Wheatstone bridge configuration on a diaphragm acting as mechanical amplifier of the strain. However this solution is satisfactorily only for sensor operations between 1 and 100 bars and a temperature range below 130°C.

For high pressure and high temperature operations, we have shown that a new type of monolithic pressure sensor can be developed using the specific properties of deep impurity states introduce by silicon dopant (so-called DX centers) in $Ga_xAl_{1-x}As$ [1,2]. For an aluminum content x lying between 25% and 40%, the DX states play a dominant role [3] in the electrical conduction so that one can observe a strong pressure induced decrease of the free carrier concentration and as a consequence a great resistance variation.

The pressure sensor consists of two sensitive layers grown by MBE on the same substrate, both having the same pressure sensitivity, but opposite temperature coefficients. The aluminum content value determine the pressure sensitivity. At a given

value of x, the temperature sensitivity of the layers can be varied over a large range by changing the doping level between 10^{16} cm^{-3} and 10^{19} cm^{-3}. The active layers are separated by undoped insulating barrier. Then the monolithic transducer is formed by two sensing resistors R1 and R2. The two resistors R1, R2 have the same pressure sensitivity (i.e. the same optimized value of x=30%) but a temperature sensitivity with an opposite sign.
Using dedicated electronics with a resolution of 10 ppm in resistance measurements, the pressure resolution ΔP in the whole temperature range above 50°C, is smaller than 50 mbar. The corresponding temperature resolution ΔT is about 2×10^{-3}°C. Unfortunately, this kind of sensor cannot be easily calibrated at ambient pressure because of the dramatic loss of pressure resolution below 50°C.

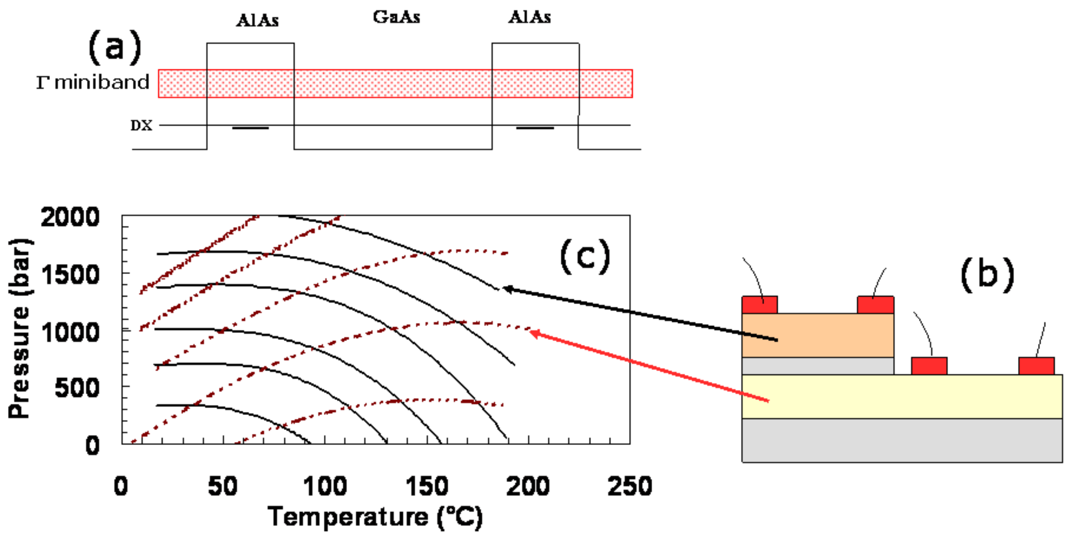

Figure1: *(a)schema of the conduction bandin a pseudo-alloy GaAs-AlAs short period superlattices; (b) Monolithic transducer formed by two sensing resistors R1 and R2- Active layers are separated by undoped insulating barrier; (c)Spine and ribs diagram for the equiresistance curves R1 and R2 in the Pressure-Temperature plane. Pressure and temperature are extracted from the measured values of R1 and R2.*

Using the same effect and the same principle, the situation is more favorable when the alloy layers are replaced by pseudo-alloy GaAs-AlAs short period superlattices (Figure 1). Indeed, it is possible to obtain thin layers in which the Al content, the thickness and the doping level are chosen to optimize the performances of the sensor.
The main advantages in using superlattices lie in the fact that Ga and Al atoms are separated and that conduction minibands, which control the conduction process, can be tuned by varying the period. The superlattices can be uniformly or selectively doped. As a consequence, the relative proportion of the dopant in the well, in the barrier and at the interfaces can be controlled. These proportions are, of course, dependent on the quality (and the thickness) of the interfaces [4].

Using appropriate electronics, the pressure sensor can work in temperatures up to 200°C with a sensitivity ratio S_T/S_P around 3bar/°C at pressures up to 2000 bars. The temperature resolution ΔT and the pressure resolution ΔP remains practically constant in the whole operating temperature range.

3. Magnetic Sensors

Some applications making use of Hall effect sensors [5], such as direct field sensing, contactless current sensing or power measurements, require more and more accurate measurements. As outlined by several groups, Hall effect sensors using a two-dimensional electron gas (2DEG) in a quantum well in III-V heterostructures show a better potential for achieving ultimate metrological performances than conventional 3D sensors. However for applications which are in need of a process technology that can integrate a Hall sensor with the electronics or in need to work under harsh conditions, other materials must to be taken in consideration. Semiconductor multilayer systems like SOI (Silicon On Insulators) are good candidate for integration, wide band gap materials like SiC and GaN are promising candidates for application in harsh environment. SOI and SiC Hall sensors are based on a conventional 3D structure (see fig. 2).

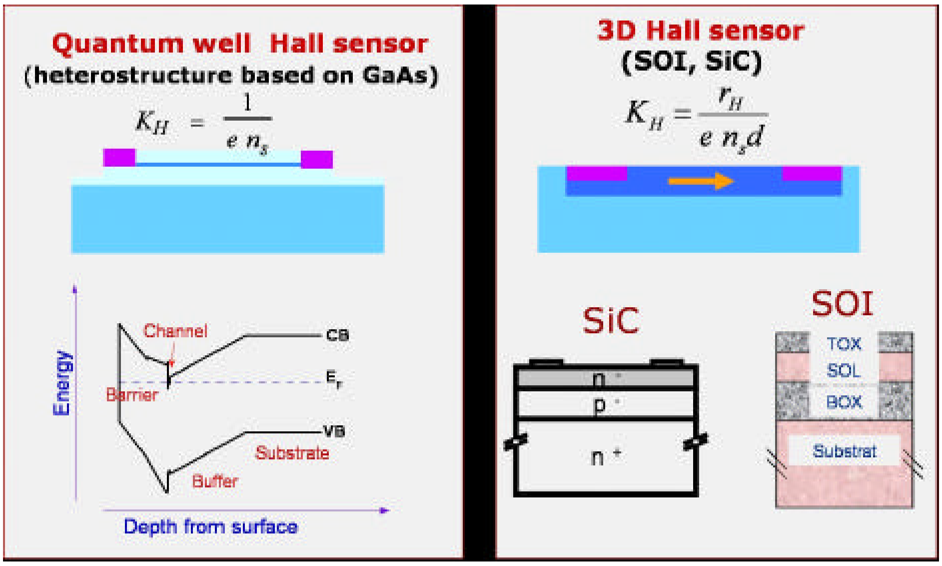

Figure 2: *(a) Two-dimensional electron gas (2DEG) in a quantum well in III-V heterostructure used as Hall effect sensors; (b) Conventional 3D structures based on SOI and SiC materials and used as Hall effect sensors.*

III-V heterostructures. Among the multiple III-V systems that can be considered, delta-doped AlGaAs/InGaAs/GaAs pseudomorphic heterostructures are particularly attractive. Indeed, they show very good performances for basic properties such as cross sensitivity K_H, its thermal drift, offset and linearity vs. magnetic field. In addition, they have the advantage of using a technology fully compatible with that used for GaAs-based microwave and ultra-rapid digital ICs, which has now become available for mass production from industrial foundries.

The epitaxial structures are grown by Molecular Beam Epitaxy (MBE) on 100 mm semi-insulating (SI) GaAs wafers. The layer sequence consists of an initial 1 ìm thick GaAs buffer, followed by an $In_{0.15}Ga_{0.85}As$ layer containing the two dimensional electron gas (2DEG) forming the active layer. It is followed by a cap layer, whose composition profile (GaAs/AlGaAs/GaAs) is adjusted in order to avoid the formation of any parasitic conduction channel in parallel to the quantum well. It includes a region with a graded Al content. Its total thickness, L_A, amounts to 2500 Å. The epitaxy is terminated by a GaAs layer. Electrons are provided to the quantum well by a Si ä-doping layer located in the AlGaAs barrier, 40 Å away from the quantum well. The Si concentration, in the 10^{12} cm^{-2} range, is adjusted in order to yield an electron density ns in the quantum well in the 8-9 10^{11} cm^{-2} range. The resulting band diagram is shown in Fig. 3. It was shown that for these devices, DX levels introduced by the Si delta-doping lie far above the Fermi level and remain fully ionized [6]. The Hall cross-sensitivity, defined by the relationship $V_H = K_H \times I_{bias} \times B$, has a value $K_H = 1/e \times n_s$ ˜720 V/AT and is 3-4 times larger than that of existing devices. The room temperature 2DEG electron mobility is about 0.72 $m^2V^{-1}s^{-1}$. The thermal drift of the electron density, defined as $S_T = 1/n_s.dn_s/dT$, is ˜ -140 ppm/K in the 200–400 K range and constant under 200 K. The magnetic resolution better than 1 nT/√Hz and an excellent linearity versus bias current and magnetic field in the 100 nT-30 T range can be achieved. Such sensors are now used for mass-market high precision electricity metering. Among the other possible applications, micro-Hall probes with a spatial resolution beyond the micrometer range can be mentioned.

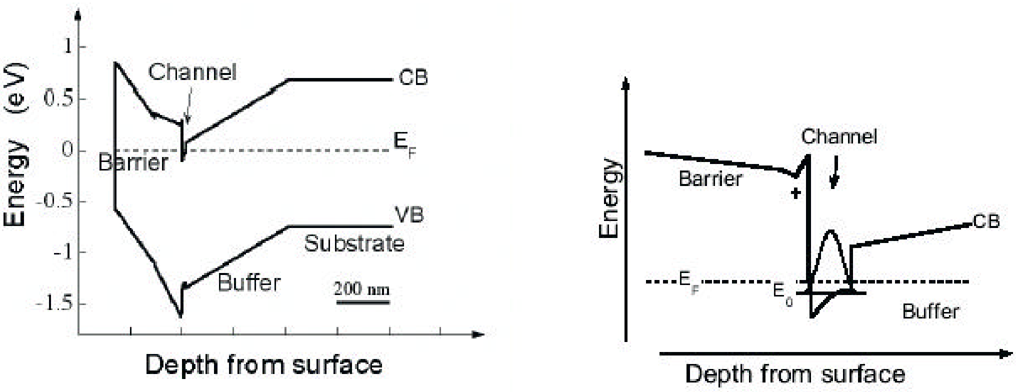

__Figure 3:__ Band diagram of a pseudomorphic AlGaAs/InGaAs/GaAs heterostructure with delta-doping and graded barrier

SOI Structure. SOI technology has now been widely demonstrated and recognized to be a mature and viable alternative to mainstream bulk Si for the realization of mixed analog/digital CMOS circuits [7], together with integrated sensors. The SOI structure is a multilayer systems. The layer sequence consists of a Si substrate, followed by a buried SiO_2 oxide (BOX), by a silicon over layer (SOL) which is the active layer and by a final top oxide.

The optimization of the Hall sensor performances is achieved by simultaneous mastering of different parameters: Hall cross-sensitivity, K_H, thermal drift of the Hall sensitivity, S_T, and Hall voltage linearity versus current supply. This can be obtained with the optimization of the thickness and the doping level of the active Si layer. The silicon layer has been thinned down to values ranging between 30 nm and 80 nm. Its n-type As doping level was between $5x10^{17}cm^{-3}$ and $2x10^{19}$ cm^{-3}.

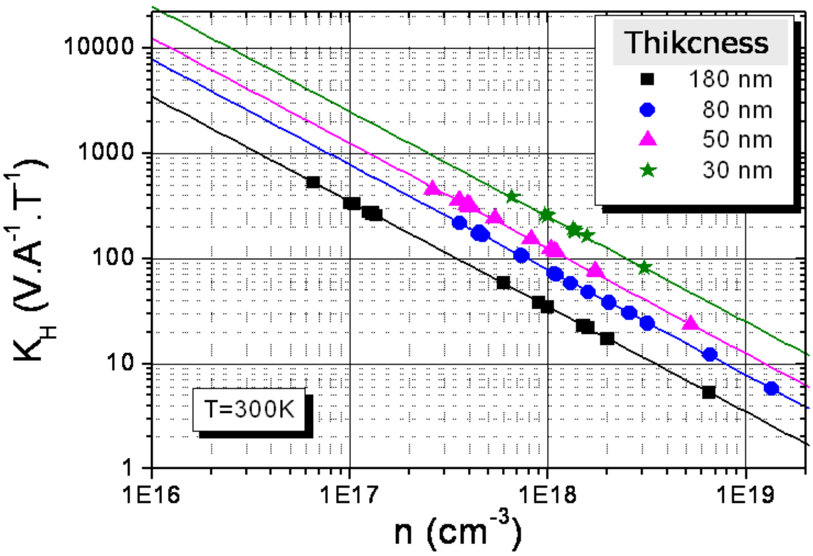

Figure 4: *Hall cross-sensitivity (K_H) versus free carrier density for different SOL thickness.*

All the useful device parameters in terms of sensor performance, like input resistance, maximum bias current, magnetic sensitivity linearity versus bias current, as well as temperature dependencies, must be in agreement with the industrial objectives and must satisfy the application requirements. Figure 4 shows the cross-sensitivity (K_H) versus free carrier density for different SOL thickness. The industrial application which first was interesting by this technology was the electricity metering. For this application, in order to obtain a good compromise in term of input resistance, of signal value and immunity to external perturbations we have chosen :

- a Hall cross-sensitivity, K_H, varying between 50V.A^{-1}.T^{-1} and 300V.A^{-1}.T^{-1}.
- with a thermal drift, S_T, around 2000 ppm/°C in the 200–400 K. range.

For our best SOI devices, the magnetic-field equivalent noise at 1 Hz is 1 µT/vHz, with a magnetic sensitivity of 67 V/(AT), provided we limit the current to the linear operation regime. This value is higher than what can be measured for III-V based sensors, because of the lower mobility in silicon. The relevance of this parameter depends however on the target application for the magnetic sensor. For higher frequency applications, the magnetic field equivalent noise depends on the value of the thermal white noise 4 $kT\ R_{out}$ and the allowable bias current. For the same device it amounts to 300 nT/vHz at 300 K. The noise figure is of little importance in the field of electrical power metering, since current and voltage noise are uncorrelated and are cancelled out by Hall multiplication in the sensor.

Therefore, SOI-based Hall devices are a good candidate in the perspective of monolithic integration of the sensor with electronics. With a suitable choice of material parameters and sensor layout, they show interesting global metrological performance, as compared to existing technological solutions.

4H-SiC Hall sensor. Silicon carbide is a well-known material for the fabrication of devices working in harsh environment. This material is also a good candidate to produce magnetic sensors working at high temperature [8].

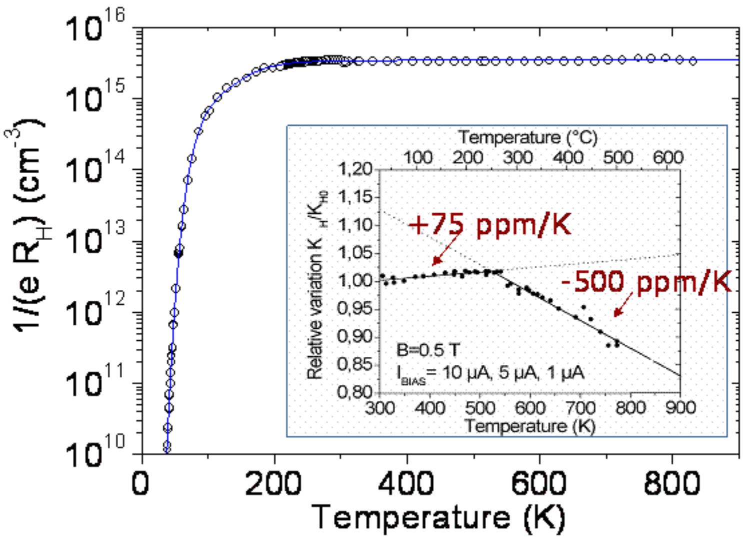

Figure 5: *Hall electron density versus temperature as measured in the 4H-SiC sensor (empty circles) and calculated (solid line).The inset shows the relative variation of the sensitivityK_{H0} of the sensor with K_{H0}= 930 V/A/T (experimental data – full circles). Lines show the thermal drift (between 300 –500 K: S_T= +75 ppm/K, between 500 –800 K: S_T= -500 ppm/K).*

In the framework of a model developed in our laboratory [9], we could determine the doping conditions in which (starting from room temperature) the material is working in the exhaustion regime. In the exhaustion regime, all donor states being emptied, the free electron density n(T) is constant. To be fulfilled, the doping level has to be lower than 5×10^{15} cm^{-3}. On figure 5, the Hall concentration of our Hall sensor demonstrator exhibits a constant value of 3×10^{15} cm^{-3} above 300 K.

As prototype sensor [10], we have used a sample with 2.4 µm thick active layer doped at a concentration of 3.5×10^{15} cm^{-3}. The magnetic field sensitivity $K_H=1/(N_s\times e)$, in which N_s is the sheet carrier density, is K_{H0}= 930 V/A/T at room temperature. The temperature sensitivity S_T is only +75 ppm/K between 300 K and 550 K and -500 ppm/K between 550 K and 800 K (see inset Fig. 5). Such small values present a great advantage since no compensating circuit for thermal drift is needed for high temperature applications.

When additional temperature knowledge is required, a bridge shape geometry can be used and, in this case, the input resistance of the device acts as a temperature sensor. Its temperature sensitivity is equal to +3400 ppm/K between 500K and 800K.

4. Conclusion

The present examples demonstrate the high potential of semiconductors for sensor technology. Indeed, intrinsic properties of some semiconductor compounds and dvice miniaturisations can offer solutions when classical concepts are not sufficient (harsh environment : high pressure, high temperature,…).

The flexibility of the epitaxial technique, the high quality of the materials, the reproducibility of the structures, the availability of mass production from the industrial founders, all these factors will contribute to further developments in other fields of applications.

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