A MEMS-SOI 3D-MAGNETIC FIELD SENSOR

Horacio V. Estrada
Centro Nacional de Metrología
División de Metrología Eléctrica
Querétaro, Qro, MEXICO 76246

ABSTRACT

A true-3D Hall sensor is reported which is fabricated based on MEMS micromachining of SOI-wafers which includes a flexible polyimide carrier so as to enable the development of a geometry-adaptable sensor when the three Hall-probes are positioned to form an orthogonally-oriented array on three faces of a non-magnetic material cube, yielding a true 3D-Hall sensor. Since the sensitivity of Hall-probes is defined by the doping level of the semiconductor material and the thickness of the Hall element, the sensitivity of each element is about the same (~100V/AT) when they are manufactured adjacent to each other on the silicon wafer where both, the doping level and the wafer thickness are near-identical.

INTRODUCTION

Even though a considerable amount of research and development have been recently reported in the literature on materials, principles and devices providing information of magnetic fields (e.g., magnetoresistive materials, diodes, transistors, microcoils), the Hall-effect is still fundamental for the implementation of reliable and precise microsensors for several technological applications and systems, based on the interaction of electric charges and magnetic fields. The basic structure of a Hall-device has been a plate-like semiconductor structure, of either rectangular of circular shape[5-6] in which four or more electrical contacts are defined to pass an electrical current and to measure the Hall-voltage generated when the moving electric charges interact with an external (dc or ac) magnetic field.

Hall probes made of semiconductor materials of high carrier-mobility are desirable since it results in higher carriers' drift velocity ($\underline{\mathbf{v}}_{\mathbf{q}}$) at a given applied electric field ($\underline{\mathbf{E}}_{\mathbf{X}}$), and thus higher Lorentz' forces ($\underline{\mathbf{F}}_{\mathbf{L,Z}}$) and higher Hall-voltages ($\mathbf{V_{H-L}}$) and magnetic sensitivities:

$$\underline{\mathbf{v}}_X = \mu\, \underline{\mathbf{E}}_X \quad \rightarrow \quad \underline{\mathbf{F}}_{L,Z} = q(\underline{\mathbf{v}}_X \times \underline{\mathbf{B}}_Y) \qquad (1a)$$

$$\rightarrow \quad V_{H-Z} = (1/nqt)\, I_X B_Y \qquad (1b)$$

That is, the Hall-voltage is only proportional to the magnetic field component that can be projected along the normal direction to the plate's width, perpendicular to the applied current (I_X), as illustrated in **Fig. 1**. That is, in-plane field components do not produce a Hall voltage across the z-axis probe terminals. The Hall voltages need to be measured with high-input impedance (micro - nano) voltmeter.

Although silicon is not a high carrier mobility material, it is however an attractive material from the processing view point, for its mature technology and long-term electrical and magnetic stability, allows the fabrication of Hall devices with stable characteristics. In addition, the use of MEMS fabrication principles on SOI-wafers, enable the manufacturing of Hall probes of precise dimensions, volume wise, as well as of high magnetic sensitivity when thin active layers, **t,** of relatively low doping, **n**, are used for this purpose.

The development of 3D-Hall probes have been explored for several years and several structures and alternatives have been reported and patented[1-4]. Some of these are based on a non-plate-like structure to implement "vertical" Hall-probes necessary for the 3D-sensors[3-5], consisting of n+ silicon pockets in an n-type square silicon block, defined in such a way to allow the measurement of the normal and parallel field separated via the external circuitry. The reported sensitivities vary based on the block size, from 10 to 800 V/A-T; and some cross-talk between the detecting points is identified for those structures[1-2]. However these are often characterized by either different sensitivity for each component[6], or by a cross-talk (cross-sensitivity) among the direction-components[2]. Moreover, these devices have the limiting characteristic of having the different sensitivity for the in-plane components with respect to the normal field components by as much as one order of magnitude.

Ideally, small magnetic probes/elements can result in better performance, higher sensitivities, higher space resolutions, lower power consumption, better integration in the overall chip/system, and overall low-manufacturing costs. The sensor presented in this paper is a new 3-D sensor implemented by three flexible "plate-like" probes, of considerable small size, integrated on a polyimide carrier which can be conformed to various geometries to yield 2D and 3D-magnetic field sensors.

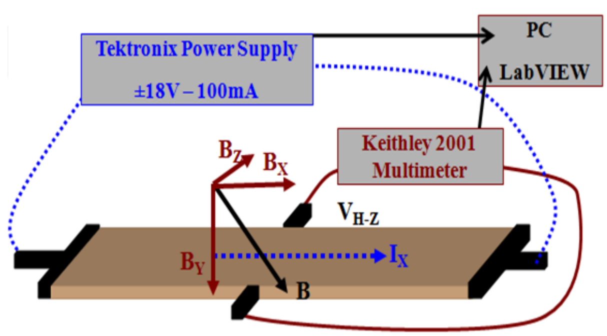

*Figure 1. Basic configuration of the plate-like Hall sensor measuring normal component of B (**B**z).*

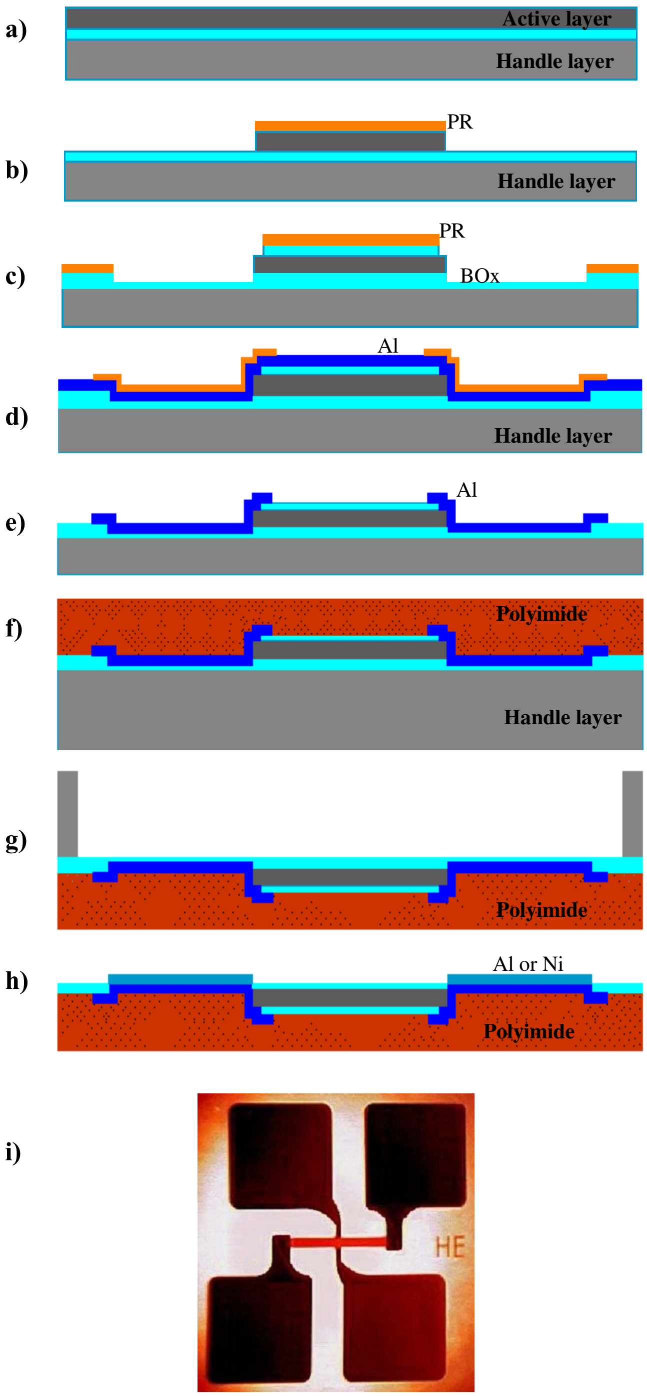

*Figure 2: Key steps leading to implementation of Hall sensors on a flexible substrate (Polyimide film). **a)** SOI-wafer; **b)** micromachining of the active layer using either wet (TMAH) or dry (DRIE) etching; **e)** patterning the Al-film needed for ohmic contacts; **f)** deposition and curing of the polyimide film; **g)** etching of the handle wafer to reach the buried oxide (B-Ox) film; **h)** final metallization of the contact pads (Ni or Al) for possible soldering or wire bonding. **i)** Top view of a completed Hall-element.*

FABRICATION AND IMPLEMENTATION OF THE 3D-SENSOR ARRAY

Flexible Hall structures have been implemented when a polyimide film is included in the fabrication process. An HD MicroSystems^{TM} polyimide coating was used to define films of about 25µm thick, serving as a flexible substrate for the carrying and transferring of the micromachined structures (Hall-probes) as well as the necessary metal and connections for their interconnection and to apply and retrieve electrical signals.

Such a flexible substrate with the Hall-probes, can be then adapted to different solid geometries, including wires cylindrical and cubic structures, so as to define arrays of 2D and 3D-sensors. The fabrication process follows a similar process used for the fabrication of flexible silicon strain gages[7] and basic Hall-probes[8], modified to define sensor arrays of 2 or 3 devices adjacent to each other.

The main steps followed for the fabrication of 2D and 3D Hall-arrays are depicted in Fig. 2, leading to the implementation of Hall sensors, shown in Fig. 3. As earlier indicated the fabrication process has been realized using p-type SOI-wafers with a 2µm active layer of about 1Ω-cm in resistivity, corresponding to a doping of about 10^{16} boron impurities/cm^3. The SOI-wafer is oxidized at ~1,100C to form an oxide layer of about 2,000A. After the first photolithographic process, the active layer is patterned to define the geometry of the Hall-probes (an elongated cross). Windows are then opened in the grown oxide to enable the metallization and the sintering of the ohmic contacts, via an Al-film. 2-3 coats of polyimide are then scheduled to achive a film of about 25µm thick followed by its curing which is carried out at ~350C. The handle wafer can be then etched away, followed by the removal of some of the buried oxide layer and a complementary metallization to provide possible soldering pads.

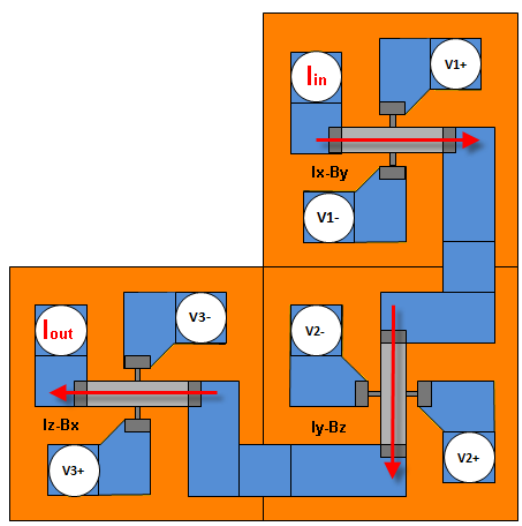

Figure 3: Layout of the Hall probes for the implementation of 3D-sensors. The flexible metal lines are included to allow the same current to flow through all elements.

Such a polyimide film becomes the flexible substrate that allows the handling of very thin specimens in a rather attractive manner. The final Hall sensors or array of sensors are then cut from the wafer as shown in Fig. 2(i). That is, each sensor consists of a rectangular element of and although 50µm wide, with the metal contact pads of 500x500µm. 2D and 3D-arrays are geometrically defined as illustrated in Fig. 3, where interconnecting metal wires can be implemented over adjacent Hall elements.

Four sets of output pads are then wired to apply the driving current and to measurement the corresponding Hall-voltages of each of the orthogonal directions, X, Y and Z, as illustrated in Fig. 4.

This direct and simple geometry allows the accurate measurement of each of the three magnetic field components simultaneously and with a relatively high sensitivity, which will be near identical for each of the axial elements. This feature is not easily obtained with hybrid 3D sensors. Furthermore, the cross-sensitivity (cross-talk) is practically negligible for this sensor array. The electrical connections require requires 8 contacts. It is recognized that the measurement point of each components is not the same in view of the overall probe dimension, however, an adequate miniaturization

CHARACTERIZATION - EXPERIMENTAL RESULTS

The ability of the reported sensor array to measure the three components of a magnetic field was established after each of the elements were characterized under controlled conditions to insure non-magnetic factors do not interfere with the targeted application. Due to the fact that the electrical properties of semiconductor materials (Si) are affected by temperature and illumination, the preliminary characterization of these sensors was performed under dark

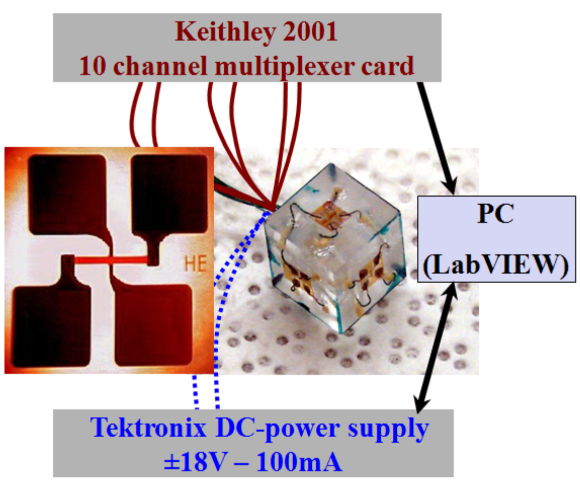

Figure 4: Image of the 3D-magnetic sensors implemented with Hall-probe arrays on a polyimide carrier on a non-magnetic cubic solid allowing the same current flows through each directional element, obtaining near identical magnetic sensitivities.

conditions and controlled temperature. With these parameters properly controlled, the magnetic sensitivity was established by monitoring the applied voltages and currents and offset output voltages that are developed across the Hall terminals under zero-magnetic field conditions. For the probes included in this study, the offset voltage was typically of the order of 1mV which remains relatively constant throughout the characterization process, and thus easy to account for under specific current levels. Fig. 5 shows the typical measured Hall voltages when the magnetic field was cycled form 2mT to 2.7T. The shown response (net Hall-voltages) is considerably repetitive over such a field range with practically no hysteresis. The regression analysis of the results (for an input dc-current of 189µA) indicate that a sensitivity of 103.3V/AT with very good linearity. Such a low currents were kept low to minimize the dissipated power across the Hall probes to insure that these remain at constant temperature.

The characterization of the 3D sensor array was performed as suggested by Fig. 4 using a Keithley voltmeter equipped with a 10 channel multiplexing conducted so as to measure the Hall voltages developed across the three orthogonal elements. The current was also monitored during the characterization process, where a relatively uniform magnetic field (over a 1cm region) was implemented using high quality permanent magnets of 1”x1” in size, with their central point accurately aligned with the center of the 3D-Hall probe array.

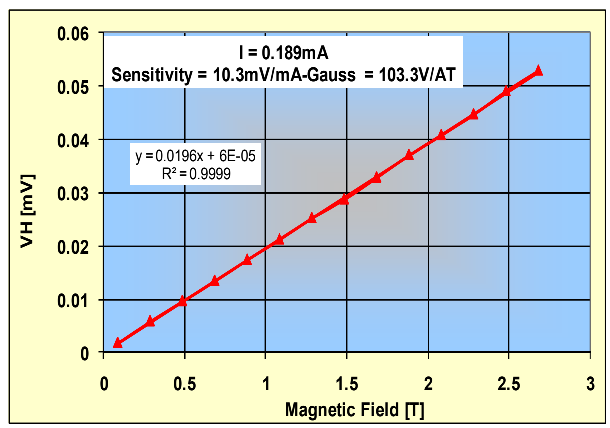

Figure 5: Typical sensitivity of each of the sensing elements integrated in the 3D-magnetic sensor. The Hall voltage corresponds to a current of about 190µA.

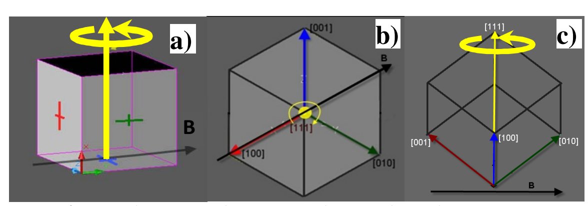

*Figure 6. Implemented protocol for the characterization of the 3D-sensors includes the rotation of the prototype around its: **a)** [100]-axis; **b)** [111]-axis, top- view; and c)[111]axis, side-view. B denotes de magnetic field.*

The 3D-sensor was then rotated around a given axis of the cubic solid itself. The ability of such 3D magnetic field sensor is demonstrated through the results summarized in Figs. 7 and 8, corresponding the measured Hall voltages for each of the orthogonal elements, X, Y and Z, upon rotation of the sensor around its [100]-axis and [111]-axis, respectively, when an current of 100uA is pass through the probes interacting with a magnetic field of 73mT.

It is clear that the maximum Hall voltage occurs when the maximum magnetic field is 90^o with respect to the current flowing through the probes. This is the case shown in Fig. 7 for either the X- or de Z-oriented probe, observed at 0^o, 180^o, and 90^o and 270^o respectively. The voltage recorded for these cases is **1.2-1.25mV**. The measured Hall voltage across the Y-oriented probe is practically zero over the entire 360^o-rotation, although a very low voltage with a sinusoidal behavior is observed.

On the other hand, when the probe is rotated around the [111]-probe's axis, a precise periodic response is observed for all three elements each of which is phase-shifted 120^o with respect to the others, shown in Fig. 8, which is the expected behavior illustrated by Fig. 7b and 7c.

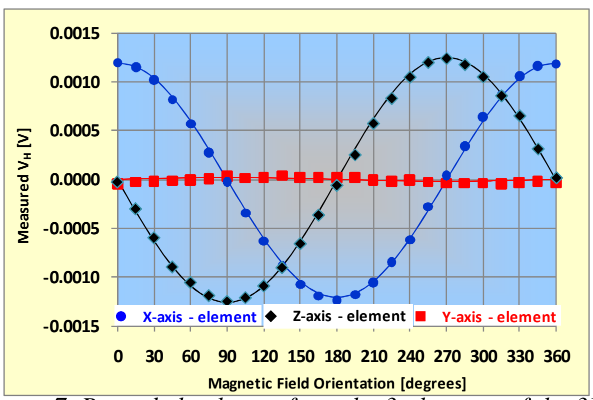

*Figure 7. Recorded voltages from the 3-elements of the 3D-Hall probe, as it is rotated around its Z-axis with the magnetic field **B** lying parallel to the X-Y plane (see Fig.6a).*

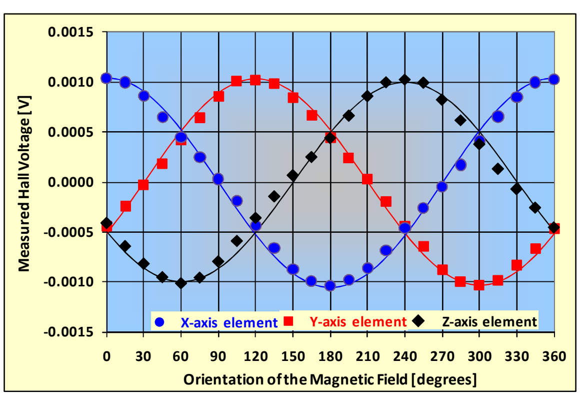

*Figure 8. Recorded voltages from the 3-elements of the 3D-Hall probe, as this is rotated around its [111]-axis, with the magnetic field **B** oriented perpendicular to this direction (see Fig. 6b-c).*

For this case, the measured maxima and minima voltages are of about 1mV for all three elements. It is also important to indicate that while the voltage one of these direction-sensors is ~|1|mV, the magnitude of the other is ~|0.5|mV. A simple numerical analysis of these voltage indicate that the magnitude of the magnetic field is that producing $(V_x^2+V_y^2+V_z^2)^{1/2} \cong 1.22$mV, which is exactly the maximum voltage recorded in Fig. 8. a configuration that may place the current and magnetic field orthogonal to each other.

CONCLUSIONS AND FUTURE WORK

The ability of the reported Hall sensor-array to measure the components of a magnetic field has been shown. The 3D-sensor configuration provides with an effective way to determine the magnitude and direction of those fields, with a device where all its elements have the same magnetic sensitivity. Improvements are being contemplated to increase the sensitivity by about one order of magnitude through the use thinner n-type wafers. The packaging of this device is also being optimized to probes 2x2mm in cross-section area.

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