# MEMS Hall Effect Sensor (May 2014)

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***Abstract*— This paper presents a Hall effect sensor fabricated at the Semiconductor & Microsystems Fabrication Laboratory (SMFL) at the Rochester Institute of Technology. The device was fabricated to have the maximum sensitivity possible with the available fabrication toolset and processes at the SMFL. The obtained resistivity of the fabricated devices was higher than expected and this affected the sensitivity of the devices. Results are shown where the devices are capable of sensing 100's of Gauss instead of the intended sensitivity of under 1 Gauss.**

***Index Terms*—Hall Effect, Magnetic Field, Length to Width Ratio.**

## I. Introduction

THE Hall Effect is named after the American physicist Edwin H Hall who discovered it in 1879 [1]. In an experimental setup he realized that a current passing through a perpendicular magnetic field will be moved with a force proportional to the product of the intensity of the magnetic field and the velocity of the charge carrier.

In his experimental setups he used metals to carry the current, and due to the high carrier concentration the effects were difficult to measure. It is why in order to take advantage of the Hall effect there is the need for materials where the charge concentration can be tailored and the device geometry can be accurately constructed. Thus, it makes sense to fabricate these devices in silicon where charges can be controlled via doping and small dimensions are easily attainable through lithographic processes.

## II. Theory

Charged particles such as electrons move in response to a force caused by electric and magnetic fields. This force is described by:

$$\vec{F} = q_0\vec{E} + q_0\vec{v} \times \vec{B} \quad (1)$$

Where F is the resultant force, E is the electric field, v is the velocity of the charge, B the magnetic field and $q_o$ the magnitude of the charge. This is known as the Lorentz force equation. Except for the charge, all other units have vector components which means that the force exerted by both the magnetic field and the electric field act in a particular direction. The electric field affects the charge carrier whether it is moving or not. On the other hand the magnetic field only affects the charge carrier if it is moving. This phenomenon is the working basis of the Hall effect.

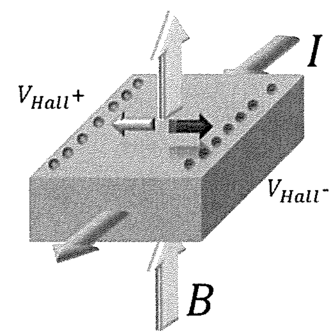


Figure 1 Hall Effect Concept

Fig. 1 shows a representation of the basic principles of the Hall Effect: first there is a moving flow of charge carries in a linear direction across the material slab. Second there is a magnetic field perpendicular to the carriers' path that forces them to either side of the device through the Lorenz force described in equation 1. This accumulation of charge to both sides of the device gives rise to the Hall voltage (VHall), which is therefore a linear function of:

a. The charge carrier velocity
b. The magnetic field perpendicular to the carrier's motion path
c. The spatial separation of the terminals where the Hall Voltage measurement is made

$$V_{Hall} = G \times \frac{I\,B}{q\,n\,t} \quad (2)$$

Equation 2 describes the quantitative relationship between the factors that give rise to the Hall voltage, where I is the biasing current, B the magnitude of the perpendicular magnetic field, q the elemental charge, n the charge density, t the thickness of the device and G is the geometric factor, which is used to take into account the short-circuit and parasitic effects that reduce the Hall effect voltage as described in equation 3.

$$G \cong \begin{cases} \left[1 - \frac{16}{\pi^2}\exp\left(-\frac{\pi}{2}\frac{L}{W}\right)\right] \cdot f\left(\frac{S}{W}\right) & \frac{L}{W} > 1.5 \\ 0.74\frac{L}{W} \cdot f\left(\frac{S}{W}\right) & \frac{L}{W} < 1 \end{cases} \quad (3)$$

Where L is the distance between the biasing contacts, W the width or distance between the sensing contacts, S the size of the sensing contact and f(s/w) a function that is close to one when S is less than 0.18*W [2]

## III. PROOF OF CONCEPT

CMOS fabrication at the SMFL requires constant tracking of implanted doses through ion implantation using the Varian 350D Ion Implanter tool. Van Der Paw (VDP) structures are included in mask design for this purpose. On a basic level a VDP structure resemble a Hall effect sensor. Using a CMOS factory class wafer with a known implanted dose, a proof of concept setup was experimented with. By sweeping a voltage across two terminals and measuring the voltage rise between the 2 perpendicular terminals the Hall voltage was measured.

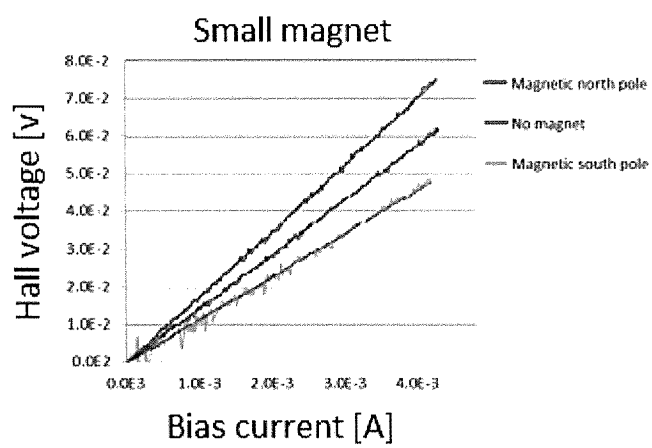


**Figure 2 Hall voltage in VDP structure**

Fig. 2 shows an IV sweep on a VDP structure. The $V_{Hall}$ was measured in the terminals perpendicular to the current bias direction and three different conditions were set: (i) no magnet, (ii) magnetic north pole and (iii) magnetic south pole. The results describe a $V_{Hall}$ reading even when there was no magnetic field present which is the Hall effect offset. The absolute value for the Hall effect measured was the same for both magnets but in different directions showing that the VDP structure can act as a Hall Effect sensor

## IV. DESIGN

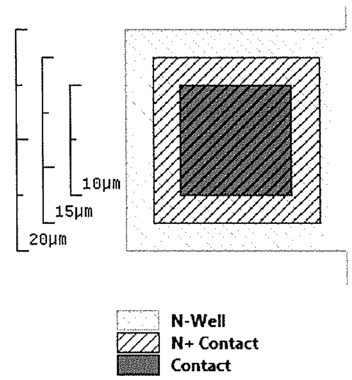


**Figure 3 Contact sizing in layout**

In order to avoid any misalignment errors being fatal to device functionality a 2.5 μm λ was used as a design rule along with a contact size of 10 μm. This allows enough room for error during lithographic and etching steps of fabrication.

Fig. 3 shows the dimensions for the contacts in the first three design layers demonstrating that any misalignment error smaller than 2.5 μm in any direction should not affect the device functionality.

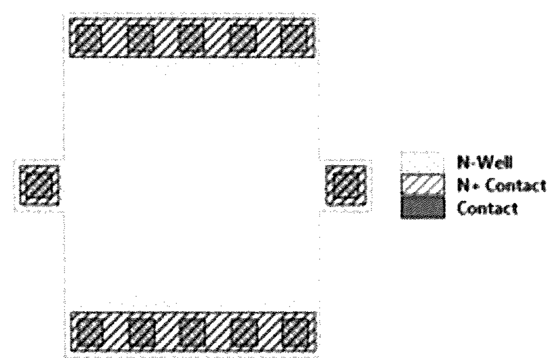


**Figure 4 Hall Effect Sensor Layout 1:1 L/W**

Since the N-type well sensing contact (S) was designed to be 20 μm, the width (W) was chosen to be 100 μm so that S≈0.18*W and f(S/W)≈1 [2] . Fig. 4 Shows the layout for the basic Hall sensor with a length to width ratio of 1:1.
The different device lengths were chosen to have L/W ratios of 1:1 1:1.5 1:2 1:2.5 1:3.

In order to investigate the effects of adding up the Hall effect of individual devices, 3 additional devices were added to the layout: (a) 2 sensors connected in parallel shown in fig. 5 (b) 4 sensors connected in parallel (c) 8 sensors connected in parallel.

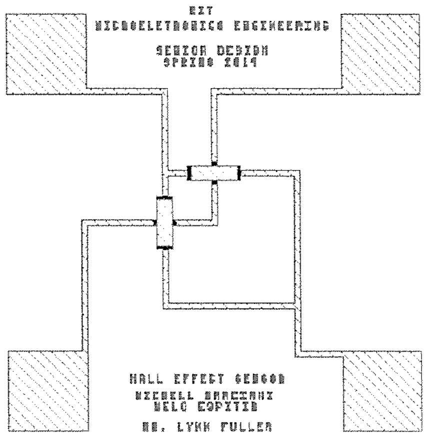

**Figure 5 parallel layout showing pads**

Also a symmetrical Hall effect device was included in the design in order to work as a symmetrical device to use with a chopper changing current and hall voltage sensing.

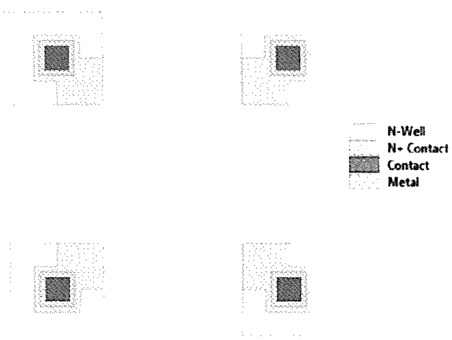


**Figure 6 symmetrical layout**

The layout in Fig. 6 matches the structure used in industry to produce high sensitivity devices. Coupled with time changing bias and sensing electrode assignments this structure can yield a high level of sensitivity and for this project was also used as a VDP structure to obtain sheet resistance measurements.

## V. FABRICATION

### *A. Simulation*

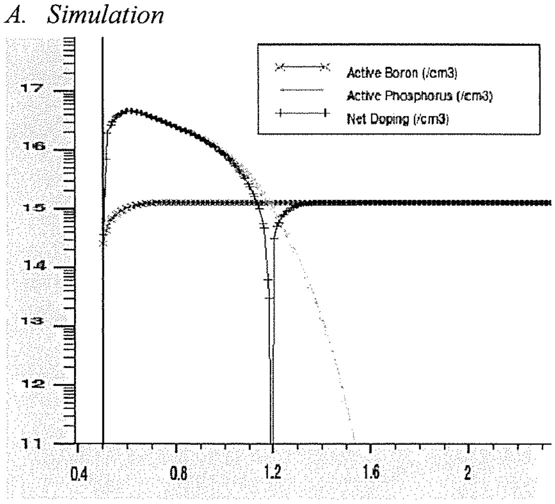


**Figure 7 Silvaco Atlas simulation of dopant profiles**

Fig. 7 Illustrates a Silvaco ATHENA simulation of fabrication process results in a junction depth of 7 µm and a sheet resistance of 4900 Ω per square

### *B. Starting Substrate*

P-type 10 Ω-cm wafer

### *C. Ion Implant through 500Å Pad Oxide*

N-type well Phosphorous $2x10^{12}$ dose 70KeV energy
P-type Field Boron $1x10^{12}$ Dose 60KeV energy
N+ Contacts Phosphorous $2x10^{15}$ Dose 60 KeV energy

### *D. Inter Level Dielectric*

LPCVD 5000Å TEOS

### *E. Contact Cuts*

One wafer was etched in HF
Wafer 2 was etched halfway through with a dry etch

### *F. Sputter Aluminum with 1 % Silicon*

## VI. PACKAGING

After wafer was diced into 3 mm x 3 mm individual dice, each device was glued to a PCB board, once there each electrode was wire bonded to an individual copper pad trace that in which a pin was soldered on. A 2 part epoxy was applied on top to protect the device and wire bonding from handling.

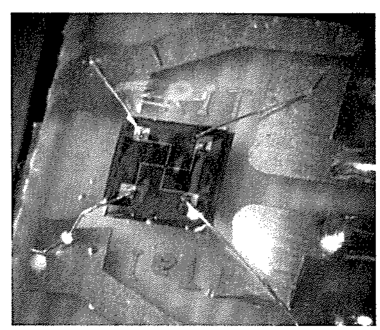

**Figure 8 Wire-bond connection**

## VII. TESTING

An electromagnet was used to create a magnetic field whose amplitude and frequency could be controlled in order to characterize the sensitivity of the Hall Effect sensors.

Initial results showed a response from the device to the magnetic field that was not controlled by the current bias. Further investigation proved that due to the high frequency of the test setup and the strength of the magnetic field and an eddy current was being induced into the device. The response measured was due to the time changing magnetic field inducing an eddy current through the copper pads. This affected the current biasing of the Hall sensor. Even at low frequencies the device did not respond to the magnetic field generated by the electromagnet.

A second wafer was tested by placing a strong Neodymium

magnet at a constant distance under the wafer under three different conditions: (i) no magnet, (ii) magnetic north pole and (iii) magnetic south pole.

A voltage was swept from 0 to 10V and the hall voltage measured for all nine devices in the central die of the wafer.

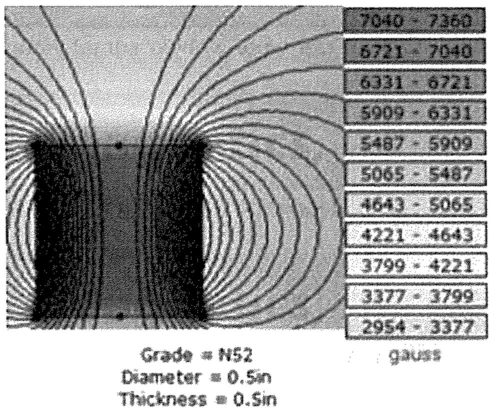


**Figure 9 Magnetic Fields of testing magnet [3]**

As illustrated by Fig. 9, due to the geometry of the magnet, the distance where the device was to be tested was crucial. Even a few millimeters of distance from the surface of the magnet can reduce the magnetic field strength by the thousands of Gauss. Also close inspection of the magnet revealed damage done to the surface which caused irregularities in the profile of the magnetic field. The same magnet was used then to test the already packaged devices and a response was measured after amplification of the $V_{Hall}$ signal.

## VIII. RESULTS

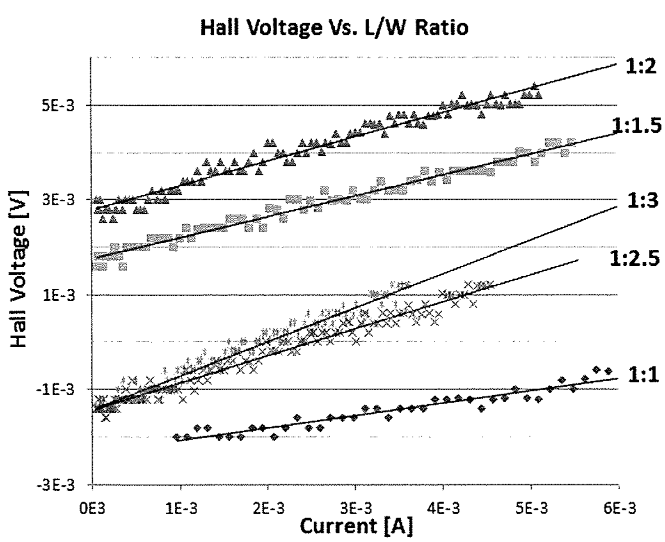


**Figure 10 Hall Voltage for different L/R ratio devices**

Table 1 Length to width ratio comparison

| L/W Ratio | Sensitivity at 5000 Gauss [V/A] |
|---|---|
| 1:1 | 26 |
| 1:1.5 | 44 |
| 1:2 | 51 |
| 1:2.5 | 57 |
| 1:3 | 72 |

The length to width ratio of the device determines not only the resistance of the device but also the geometrical factor shown in equations (2) and (3). The device sensitivity goes up as the length of the device increases, and the offset voltage is reduced. This is due to the fact that the contacts are more likely to be placed in equipotential locations in a larger device than in a short device. All devices show a linear relation between the bias current and the Hall Effect measured in the range of 0 to 10 Volts, due to fabrication errors there is a large difference in resistance both devices within the die and different dice within the wafer. A misalignment error is not probable to be the cause due to the high accuracy of the stepper used for the lithographic steps. This large offset in resistance could have been caused by non-ohmic contacts between the aluminum deposited and the N+ contact areas even though there was a sintering step performed at 450 °C, but if the gas flow was not the desired it could have not allowed for the native oxide to be consumed by the Aluminum during the sintering step. The devices that were chosen to be packaged and tested came all from the same die in the center of the wafer that showed the lowest sheet resistance and was constant within the die to ensure that each device could be compared to each other.

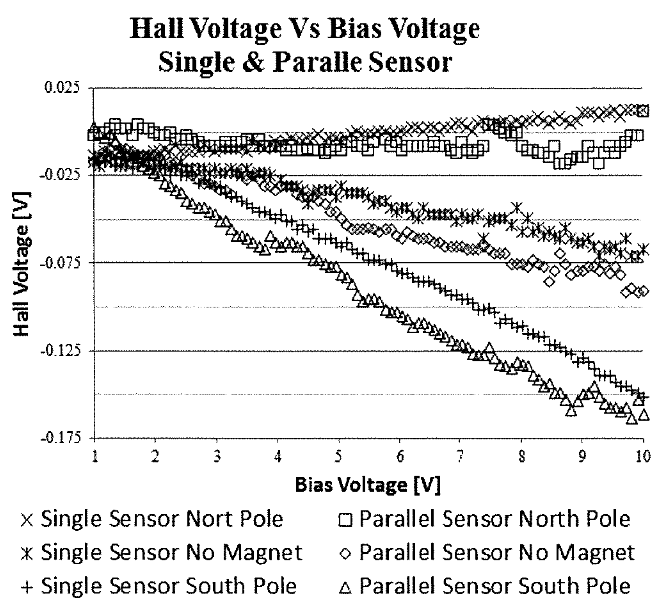


**Figure 11 Single and parallel sensor**

**Table 2 Single device to parallel sensor comparison**

| Magnet | Sensitivity at 5000 Gauss |
|---|---|

| Position | [Hall Voltage/Bias Voltage] | |
|---|---|---|
| | 1:3 L/W Single Sensor | 1:3 L/W 4 sensors in parallel |
| North Pole | $9.30\text{x}10^{-3}$ | $8.90\ \text{x}10^{-3}$ |
| South Pole | $9.30\text{x}10^{-3}$ | $8.40\text{x}10^{-3}$ |

Due to the low yield of the first batch of wafers a comparison could only be done for a single device of L/W ratio 1:3 to a device comprised of four Sensor connected in parallel to add up the hall voltages. The results shown in fig. 11 yielded a low difference between the sensitivity of these device configurations. In order to increase the sensitivity each device connected in parallel must be biased independently [2], due to testing and time constraints the design was implemented so that all parallel devices would be biased through the same pad. This is likely to be the reason why the difference is not as noticeable as previously expected.

## IX. CONCLUSION

Hall Effect sensors were designed, fabricated, packaged and tested using CMOS fabrication steps available at the SMFL, due to processing errors the resistance within devices and within wafers was not constant allowing only a few devices to be tested and compared to each other. The testing setup and device packaging did not take into account the induced current caused by using an electromagnet to characterize the devices so a simple test using a permanent magnet was used instead. Although not sensitive enough to measure magnetic fields under 1 Gauss, the devices proved sensitive enough to detect magnetic fields in the range of 100's of Gauss.

## X. ACKNOWLEDGEMENTS

I would like to thank Dr. Lynn Fuller for his guidance and support during the entire scope of the project, to Karine Florent for her help during the fabrication stages, to Joshua Locke for his help during the testing and packaging of the devices and to Dr. Rommel and Matthew Filmer for their feedback and editing on this document.

## REFERENCES

[1] R S Popovic, *Hall Effect Devices.* Belmont, CA: Wadsworth, 1993, pp. 2,

[2] J.-B. Kammerer1,a, L. H´ebrard1, V. Frick1, P. Poure,b, and F. Braun1 *Hall effect sensors integrated in standard technology and optimized with on-chip circuitry*, European Journal of applied physics. 36, 49–64 (2006)

[3] http://www.kjmagnetics.com/magfield.asp?pName=D88-N52

[4] Fani Liakou , *Galvanically Isolated Wide-Band Current Sensors Dissertation.* Department of Electrical and Computer Engineering, School of Engineering of the University of Thessaly, Greece.