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Development of Micro-Hall Sensors for High Power Electronics Applications

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in the

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College of Engineering
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by

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By

Thomas Rembert
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Abstract

In this project, we are looking to explore the characteristics of GaAs/InGaAs/AlGaAs and GaAs/AlGaAs Hall Effect sensors for use in power electronics monitoring circuitry. Hall sensors have the ability to detect the presence of magnetic fields orthogonal to the sensor surface. In order to fully understand the response of such a sensor, I performed complete micro-Hall sensor fabrication and characterization, which includes (i) fabrication of Greek cross sensors with lateral dimensions of 120 µm (ii) contact optimization (iii) sensitivity measurements (iv) noise spectra measurements. Basic studies of sensor response to high current circuit board traces were also performed on the sample. Further suggested studies include integration of magnetic field concentrators in order to focus magnetic fields on the sensor surface. Overall, continued studies of high currents, pulse response, and magnetic field concentration will lead to a better understanding of the application of these sensors to power electronics current sensing circuits.
Introduction

In today’s power electronics, it is not uncommon for circuits to have between tens or hundreds of amps flowing through them. While these high currents are necessary to perform desired operations, changes or defects in the circuit resulting in increased current or current being redirected to areas it’s not supposed to be in may severely damage or even destroy whatever system being used. Because of this, it is necessary to develop methods of monitoring the current flow in such high-powered systems.

Previous methods of current sensing that have been implemented have simply involved a resistor. Current monitoring can be performed by looking at the voltage across that sensing resistor and then comparing that voltage to the expected voltage or a threshold voltage to determine if the current is too high or low. While this method does work, it has many drawbacks. For example, too high of a resistor value for sensing will lead to more power dissipation, or more \( I^2R \) losses, through that resistor. Also, even with a small resistor value, the losses through that resistor are still great due to the high currents used by the system. It is this power loss that is the inherent flaw of using a resistor for current sensing. Instead, such a sensing network can be replaced by a Hall Effect sensor (Hall sensor).

A Hall sensor is able to do what a resistor cannot—monitor the current through the circuit without drawing any power from the circuit. Instead, the Hall sensor operates on its own low-power circuit, separate from the power electronics circuit. The sensor works by harnessing the magnetic field produced by the current flowing through the wire. This magnetic field creates a Hall voltage on the sensor, which can then be measured and
run through a comparator to determine the state of the system and what actions should be taken (i.e., shut off power supply to avoid damage of elements due to high currents from short-circuiting). Such a sensor would eliminate the need for power-dissipating elements to sense the current in a circuit.

Hall sensor structures are created using such technologies as molecular beam epitaxy (MBE), which allows for material growth precision on the atomic scale with the ability to control single layers of atoms at a time. Intricate structures can be constructed by varying the materials used along with their individual thicknesses. For example, semiconductor materials with varying band gap energies can be used. A semiconductor has two energy bands, or large aggregate of energy states, called the valence band and conduction band. In the case of a pure conductor, the conduction and valence bands overlap, so it is easy for an electron to leave the valence band and immediately enter the conduction band where the electron can conduct to different atoms through the material. Semiconductors, on the other hand, have a small energy gap between the valence and conduction band. Thus, the electrons need additional energy to transition into the conduction band. This energy, equivalent to the energy between the two bands called the band gap energy, is usually on the order of 1 or 2eV, or around $2 \times 10^{-19}$ J. Using two different types of semiconductor materials with different energy band gaps can useful for containing electrons in specific states. For example, a layer of Indium Gallium-Arsenide (InGaAs) grown between two layers of Gallium-Arsenide (GaAs) has a lower energy band gap than the GaAs layers, causing carriers to reside in the lower energy InGaAs conduction band. If the InGaAs layer is made very thin, the electrons become restricted to that plane of lower energy InGaAs. This sort of two-dimensional state in which an
electron is confined is called a quantum well (QW). Using this knowledge of material growth and quantum confinement with varying semiconductor materials, it is possible to create incredibly unique structures with interesting fundamental properties and purposeful applications.

My studies of such a sensor for this type of circuit monitoring were done with GaAs/InGaAs/AlGaAs and GaAs/AlGaAs quantum well Hall sensors. While these studies do entail the characterization of GaAs/InGaAs/AlGaAs and GaAs/AlGaAs Hall sensors and their potential application to such a system, long term studies of materials more stable at high temperatures, such as GaN, may also be studied. With the eventual use of GaN Hall sensors, it may be possible to have this sort of passive current measurement in high temperature environments of power electronics.
Theoretical Review

The first step in understanding how a Hall sensor works is by first understanding the Hall Effect. The Hall Effect is an effect in which a voltage can be produced across a sample by deflecting moving electrons in an electrical current with a magnetic field normal to the sample. Based on Figure 1, a sample is being biased with a current \( I \) through the left terminal such that an electric field \( E_c \) is produced across the sample.

![Diagram of a sample experiencing the Hall Effect.](image)

This causes the velocity of the electron, or drift velocity \( v_d \), to be in the opposite direction of \( E_c \) because of its negative charge. As the electron moves from the right terminal to the left terminal, the applied magnetic field deflects the electron due to the Lorentz force described by:

\[
\vec{F_L} = q[\vec{v}_d \times \vec{B}]
\]  

(1)

which takes the cross product of the electron velocity and the applied magnetic field multiplied by the charge of the electron. This force causes electrons to build up on the front terminal, indicated by minus signs on the figure. As electrons build up and create a difference in electric charge, and electric field \( E_{H} \) is produced from the back of the
sample to the front. Consequently, this field exerts a force $F_H$ on the electrons as well:

$$
\vec{F}_H = q\vec{E}_H
$$  \hfill (2)

However, as this force begins to balance out the Lorentz force, $F_L$, there is less deflection of electrons by the magnetic field due to the opposing Hall force. Eventually the Hall force increases to the magnitude of the Lorentz forces, stopping the deflection of electrons, such that:

$$
\vec{F}_H + \vec{F}_L = 0
$$  \hfill (3)

And by equating these two forces and substituting their original equations, the electric charge $q$ cancels to end up with the following relation:

$$
\vec{E}_H = -\vec{v}_d \times \vec{B}
$$  \hfill (4)

The current $I$ through the system is defined as the number of charges per unit time passing through the sample at a terminal. This can be mathematically expressed as the following:

$$
I = Aqn\nu_d
$$  \hfill (5)

where $A$ is the cross sectional area of the terminal, and $n$ is the carrier density. The carrier density is expressed in terms of a cubic volume, so multiplying it with the cross-sectional area would provide the number of carriers in a slice of the sample parallel to the terminal.
The remaining carrier density dimension is the direction of the drift velocity. Multiplying the number of carriers in the parallel slice with these two values results in the number of carriers passing terminal area $A$ per unit time. The charge of the electron is then factored in to give the expected result of current, coulomb per second. Solving for the drift velocity in this current equation, the original equality equation can be replaced by:

$$\vec{E_H} = -\frac{1}{Aq}\left[I \times \vec{B}\right]$$  \hspace{1cm} (6)

Assuming the magnetic field is orthogonal to the surface, the cross product reduces to simple multiplication. The cross-sectional area is then reduced to its components of sample thickness $t$ and sample width. The width is then multiplied with $E_H$, resulting in the voltage across the sample from back to front, resulting in:

$$V_H = \frac{R_H}{t}IB_{ort} \text{, where } R_H = -\frac{1}{qn}$$  \hspace{1cm} (7)

where the $V_H$, or Hall voltage, can be measured across the sample surface. And from the above equation, it is clearly seen that the Hall voltage and applied magnetic field have a linear relationship, assuming all other factors constant.

Initial studies of group III-V semiconductor material Hall sensors were first studied at a fundamental level by looking at the effects of doping on the magnetic field response of the material [1]. Additionally studies on Hall sensors have been performed to see the effects of physical changes of the system on the Hall voltage output as well as
sensitivity. The absolute sensitivity of a Hall sensor is defined as the rate of change in Hall voltage response to the applied magnetic field, or \( S_A = dV_H/dB \). In particular, the structures used in this work are quantum well (QW) structures, rather than traditional bulk material. This is because the use of a QW structure with remote doping greatly decreases the amount of electron scattering in the channel, leading to much higher values of room temperature mobility, unlike bulk materials that have impurities throughout the bulk, causing more scattering and reduced mobility (Figure 2).

It was shown that increasing the strain between layers of the QW structure can actually increase the sensitivity of the device as well as provide a reduction in low-frequency noise \([3]\). Additionally, varying the materials used and the composition of these materials have been shown to vary the sensitivity of the system as well \([4]\). Overall, exploration of the physical characteristics of these grown structures has made it possible to engineer sensors with as small as nano- and pico-Tesla sensitivity \([5,6]\).

Using noise spectroscopy, it is possible to look specific properties of the Hall sensor such as detection limit. In addition these studies will allow us to characterize these devices in terms of its reliability and quality by probing defect states in the bulk of Hall effect sensor and by measuring flicker noise and determine the Hooge parameter. The frequency spectrum of the Hall voltage points to these specific characteristics. For example, from the frequency response, it is possible to isolate specific sites of generation-recombination effects, or sites of defect states in the Hall sensor, which add noise to the
system [7,8]. Additionally, the noise spectroscopy provides information on the signal to noise ratio, which is directly related to the detection limit of the sensor. Also, the Hooge parameter, a parameter that is essentially a figure of merit for the Hall sensor material, can be determined by studying the frequency spectrum of the noise. Further details regarding the specific applications of the noise frequency spectrum to these sensor characteristics will be discussed in a later section.
Experimental Techniques

The main experimental techniques used in this project were structure growth, Hall measurements, sample processing, contact resistance optimization using transmission line model (TLM) structure, sensor calibration, noise measurements, and pulse detection. As mentioned in the previous section, the Hall sensors are grown using solid-source MBE on a semi-insulating substrate. Deposition of a GaAs buffer and fifteen repetitions of an AlGaAs/GaAs superlattice act as a filtering mechanism to reduce crystal defects, providing a very high quality surface on which the subsequent quantum well layer can be grown (Figure 3). Additional carriers were added by remotely doping the structure barrier layer so as to not have ionized impurities close to the quantum well channel, which would lead to increased electron scattering, reducing the mobility of the structure.

For the Hall measurements of the structure, it is possible to obtain the carrier density, conductivity, and mobility. This is done by measuring the Hall voltage produced across the sample. Again, in the Hall Effect measuring system setup, the sample thickness, current bias, and applied magnetic field are all known, and the measured value is the Hall voltage $V_H$, thus making it possible to solve for $R_H$. Knowing $R_H$ and the charge of the electron, the carrier density can be found. Finally, after measuring the resistivity of the sample, which is defined as the inverse of the conductivity $\sigma$, it is
possible to find the mobility as governed by:

\[ \sigma = q \eta \mu \]  \hspace{1cm} (8)

Hall measurements were performed with a Lakeshore Hall measurement system. Samples were loaded into the cryostat and pumped down in preparation for temperature dependent studies. The process began with room temperature measurements of conductivity, mobility, and carrier density at an exposure of 5 kGauss magnetic field normal to the sample surface. The cryostat was then cooled, and subsequent measurements were taken every 10 K down to 8 K.

In terms of processing, the Hall bar structures used for measurements were fabricated using optical photolithography. AZ4330 photoresist was spun onto each samples at a rate of 5000 rpm and baked for three minutes at a temperature between 110-115 °C. Samples were then carefully positioned under an optical photolithography mask containing Greek cross Hall bar structures (see Figure 4). After exposing the mask-covered samples with ultraviolet light for twelve seconds, the samples were developed in AZ400K developer for two minutes. At this point, the developer is able to remove all of the photoresists that was exposed to ultraviolet light, leaving us with the “shadow” of the mask pattern we placed on top of our sample. The samples were then etched into the GaAs buffer layer of the structure by using a 2 H₃PO₄: 2 H₂O₂: 50 H₂O etching solution and again prepared for photolithography. Because the
portion of the sample that was not exposed to ultraviolet light still has photoresist on top of it, these portions are not etched. Instead, the etching only occurs on the exposed portions of the sample. After etching, the samples were then aligned to the appropriate Hall bar contact mask, exposed and developed. This process causes the only the areas used for contacts to be exposed, leaving the rest of the sample covered in photoresist. The samples were then mounted inside the e-beam evaporator for contact deposition. Contacts were formed by depositing 75 nm of AuGe, 15 nm of Ni, and 200nm Au on top of the sample. An ultrasonic acetone bath was then used to remove the AuGe/Ni/Au deposited on the unexposed portions of photoresist. Because the acetone removes photoresist, the metals deposited on top of the photoresist were removed, leaving only the contact metals that were directly deposited onto the sample surface. Figure 5 shows a diagram of the processing steps. At this point, the contacts have been deposited, and the optimal contact resistance is then achieved.

The contact resistance between the deposited metal contacts and the semiconductor material must have Ohmic contact in order for the Schottky barrier to be reduced, allowing for lower detection limit. In order for the sensor to be linear, a low contact resistance is needed. In order to
decrease this contact resistance, Ohmic contact is necessary. Sample contact resistance is lowered by the diffusion of the metal contacts into the semiconductor material by means of annealing. Samples are annealed multiple times at temperatures varying from 420-450°C for 2-5 min to insure proper diffusion of the metal contacts into the semiconductor material to optimize contact resistance. After this, individual structures were then cleaved and mounted into chip carriers for analysis.

For sensor calibration, sensors are loaded between the poles of an electromagnet, and the produced Hall voltages by varying a magnetic field from -2500 to 2500 Gauss were recorded. Recalling the previous equation for Hall voltage, the resulting plots should be linear, assuming a constant bias current through the sensor. These measurements were performed at varying bias current and bias voltage levels to see the effects of different sensor bias conditions on magnetic field sensitivity for the sensor.

For noise measurements, frequency spectrum information was gathered from the range of 4 Hz to 100 kHz to see the frequency dependencies on noise signal generated from the sensor. This spectroscopy was done at varying bias current conditions of the sensor. Changing the bias conditions and looking at the noise spectra can provide information on defect states or traps that may arise from increased bias conditions, potentially exciting additional carriers from defects states or exciting electrons into higher energy traps.

Preliminary studies of high current (around 7 A) circuit board magnetic response were done by placing the Hall sensor on the trace of a direct-bond copper circuit board. The Hall sensor was biased with an external power supply up to 1 mA with the circuit board being biased at a constant 7 A. Due to low magnetic fields produced, further
measures on magnetic field concentration or amplification, as well as studies of optimal sensor placement on the circuit board, will be necessary in order to maximize sensor effectiveness.
Contact Optimization

Contact resistance is analyzed by means of the Transmission Line Model (TLM) structure, as seen in Figure 6. With this pattern, it is possible to measure the resistance between two contacts along the channel, using progressively larger channels each time. The resistance consists of the effective resistance of the semiconductor/metal interface created by the contacts as well as the resistance of the total semiconductor channel between the two contacts being used for measurement. This relationship of the total resistance measured in the TLM structure with increasing channel distances is governed by the following equation:

\[ R = 2R_C + r_s \frac{l_i}{w} \]  \hspace{1cm} (9)

where \( R_C \) is the contact resistance, \( r_s \) is the sheet resistance of the semiconductors material between the contacts, \( l_i \) is the distance between individual contacts, and \( w \) is the width of a single contact [9]. Plotting these values and finding the y-intercept of these values should denote the resistance of the two contacts without semiconductor between them, or twice the contact resistance (Figure 7). Once found, the contact resistance value can be decreased by annealing the sample, causing more diffusion of the metal into the
semiconductor material, giving lower contact resistance because of the decrease of the Schottky barrier. Because the contact resistance as a function of annealing and diffusion follows a U-shape, annealing is performed until the measured contact resistance increases from the previously measured value [9]. At this point, optimal contact resistance has been achieved and the Hall sensor can be studied further.

For example, consider sample SE210. Figure 8 shows the measured resistances as a function of distance between contacts.

![Graph showing resistance measurements as a function of distance between contacts for SE210.](image)

**Fig. 8:** Resistance measurements as a function of distance between contacts for SE210.
This result occurred after the following sequence of annealings: two minutes at 420°C, one minute at 420°C, and one minute at 430°C. From the linear fit of the data, the y-intercept is $2R_C = 289.39 \, \Omega$, resulting in an individual contact resistance $R_C = 144.659 \, \Omega$. 
Sensitivity Measurements and Sensor Calibration

In order to calibrate the sensors, it is necessary to look at the Hall voltage produced at varying magnetic field exposure while biasing the sensor. In terms of biasing, the sensors can be biased at either constant current or constant voltage. To determine the ranges at which the sensor should be biased, basic I-V measurements were done to see the Ohmic limits of the sensor due to contact resistance. After this, each sample was exposed to a magnetic field sweep normal to the sample surface at each of these bias conditions. The result shows the Hall voltage produced for a given magnetic field sweep at a given bias condition.

The absolute sensitivity of these sensors is defined as the change in Hall voltage with respect to the change in applied magnetic field, or $dV_H/dB$. This is determined by creating a linear fit of the voltage response at each bias level and recording the slope of this line. These values are then plotted as a function of bias to see the effects of increasing bias on sensitivity of the sensor. The individual responses for samples SE166, SE167, SE168, and SE210 and their absolute sensitivities at constant current are shown below.
Fig. 9: Hall voltage response of sample SE166 while biased at constant current.

Fig. 10: Hall voltage response of sample SE167 while biased at constant current.
Fig. 11: Hall voltage response of sample SE168 while biased at constant current.

Fig. 12: Hall voltage response of sample SE210 while biased at constant current.
The supply-current related sensitivity, $S_I$, is inversely proportional to the carrier concentration in our system, as governed by the following equation:

$$S_I = \frac{S_A}{I} = \frac{G}{qn_{2D}}$$  \hspace{1cm} (10)$$

where $G$ is the geometrical correction factor the Hall sensor, $q$ is the electric charge, and $n_{2D}$ is the sheet carrier concentration in the quantum well channel. The linear behavior of the absolute sensitivity with respect to bias current implies a constant slope, which means that the carrier concentration is constant in the system, which is necessary for the Hall sensor to function appropriately. Any nonlinearities at higher biases could affect the
linearity of the sensor. There can be different reasons involved such as defects, hot carrier phenomena, etc.

In addition to current biasing, the Hall sensors can be biased at constant voltages. Similar studies of sensor response to magnetic fields were done at constant voltage biases, and results for samples SE166, SE167, SE168, and SE210, as well as absolute sensitivity, are reported below.

Fig. 14: Hall voltage response of sample SE166 while biased at constant voltage.
Fig. 15: Hall voltage response of sample SE167 while biased at constant voltage.

Fig. 16: Hall voltage response of sample SE168 while biased at constant voltage.
Fig. 17: Hall voltage response of sample SE210 while biased at constant voltage.

Fig. 18: Supply-voltage-related sensitivity for samples SE166, SE167, SE168, and SE210.
The absolute sensitivity of the magnetic sensor at biasing conditions is given by:

\[ S_A = G v W \]  

(11)

where \( G \) is the geometrical correction factor the Hall sensor, \( v \) is the electron velocity, and \( W \) is the width of the Greek-cross active area of the sensor. The plateau effect seen in this \( S_A \) plot is explained by the saturation velocity of the semiconductor. As electric field increases, the electrons are continually accelerated by the applied electric field. Due to interaction between the electrons and phonons, part of the kinetic energy of the electrons is transferred to the lattice and results in heating. At high biases, this leads to drift velocity saturation.

As seen in the Hall voltage versus magnetic field and absolute sensitivity versus bias plots, sample SE210 showed linear response with small offset and the highest \( S_A \) compared to other samples, respectively. Thus, further studies were performed on the SE210 sample.
Noise Measurements

There are three main sources of noise in the Hall voltage output of these sensors: $1/f$ noise, generation-recombination (G-R) noise, and thermal noise. The $1/f$ noise is a result of the natural fluctuation of the conductivity of the system [10]. Recall that the conductivity is defined as $\sigma = en\mu$, so any fluctuations in the conductivity would be a result of changes in the carrier concentration or mobility. G-R noise results from the generation of carriers from defects states near the conduction band or the recombination of electrons into one of these states. Thermal noise is a frequency independent source of noise that is present in all systems due to the random thermal motion of electrons. Together, these sources combine to form a complete description of the noise (Fig. 19) which is given by:

$$S_{V,\text{noise}} = \frac{A}{f} + \frac{B}{1 + (f/f_0)^2} + 4k_BT\tau, \quad \text{where} \quad A = \frac{aV^2}{N}$$

Fig.19: Plot showing the three different sources of noise ($1/f$, G-R, and thermal) on a typical frequency spectrum of voltage noise [9].
$S_{V,\text{noise}}$, is defined as:

$$S_{V,\text{noise}}(f) = \frac{\overline{\Delta V^2_{\text{noise}}}}{\Delta f}, \text{ where } \Delta f = \text{bandwidth}$$  \hspace{1cm} (13)

The first component in Eqn. (12) represents the $1/f$ noise, where $A$ is the magnitude of the $1/f$ noise, which is composed of the Hooge parameter $\alpha$, the square of the voltage across the sensor $V^2$, and the number of carriers $N$. Further discussion of these components will occur later in this section in which the Hooge parameter is determined for this sensor. The second component represents the G-R noise, where $B$ is the magnitude of the G-R noise and $f_0$ is related to the time constant $\tau_0$ of a G-R process as $f_0 = 1/2\pi\tau_0$. The last term represents the thermal noise, with $k_B$ as Boltzmann’s constant, temperature $T$, and sample resistance $R$. While analysis of this noise spectrum can be used to characterize defect states and G-R time constants, the focus of these noise studies were to determine the Hooge parameter, $\alpha$, of the sensor.

In order to determine the Hooge parameter, it is necessary to perform noise spectrum analysis at varying bias conditions for the circuit. The bias circuit for this experimental setup consisted of a 24 V battery connected in series with a variable resistance and the Hall sensor. Figure 20 shows the frequency spectrum of the Hall voltage noise at varying bias conditions.
With increasing bias, the magnitude of the noise level increases. Additionally, with increased current, it is possible to see the development of additional G-R noise components as the appearance of additional Lorenztians in the spectrum at high frequencies. This effect can be most noticeably seen for the highest-biased sample. However, for the Hooge parameter, only the magnitude of the 1/f noise is necessary. Non-linear fits were performed for each of these bias conditions, and the magnitude of $A$ was extracted for each condition. Figure 21 shows an example non-linear fit for the data.
From this fit, the fitted value of $A$ can be extracted. Again, this was done for each bias condition. Recalling that $A$ is defined as $A = \alpha V^2 / N$, it can be observed there is a linear relationship between the value of $A$ and the square of the voltage across the sample, assuming a constant Hooge parameter, $\alpha$, and constant number of carriers, $N$, in the system. Thus, by plotting $A$ against the square of the voltage across the sample, it is possible to obtain the Hooge parameter via the following relation:

$$\alpha = \text{slope} \times N$$

(14)
where the square of the voltage is determined by the biasing condition of the circuit, assuming a sample resistance of $R = 4.5 \, k\Omega$. Additionally, the number of carriers $N$ can be determined by the following equation:

$$N = \frac{L^2}{eR\mu}$$

(15)

where $L$ is the distance between contacts, $e$ is the fundamental charge, $R$ is the sample resistance, and $\mu$ is the mobility. In our case, $L = 120 \, \mu m$. Again, the sample resistance value used is $R = 4.5 \, k\Omega$, and the room temperature mobility of the GaAs/InGaAs/AlGaAs QW structure to be $\mu \approx 5700 \, cm^2/(Vs)$. Figure 22 shows a linear fit of the $A$ values obtained at varying bias conditions.

![Figure 22](image_url)

Fig. 22: Plot of $1/f$ noise magnitudes at varying bias conditions against the square of sample voltage. The resulting slope of the fitted line is proportional to the Hooge parameter.
Using the fitted line slope and the calculated number of carriers in the system, the Hooge parameter value was determined to be \( \alpha \approx 5.71 \times 10^{-5} \), which is comparable to previously studied measurements of the Hooge parameter of GaAs/InGaAs/AlGaAs and GaAs/AlGaAs QW Hall sensors [10].

Another important parameter of the Hall Effect sensor is its detection limit. The detection limit is directly related to the signal-to-noise sensitivity (SNS) of the Hall sensor by the following relation:

\[
B_{DL} = \frac{1}{SNS} \quad \text{where} \quad SNS = \frac{S_A}{V_{noise}}
\]  

(16)

where \( S_A \) is the absolute sensitivity of the sensor and \( V_{noise} \) is the average voltage noise as determined by \( V_{noise} = \sqrt{S_{V,noise}(f)\Delta f} \) within the bandwidth \( \Delta f = 1 \) [10]. From Figure 20, the value of noise at 100 kHz for the current bias of \( I = 397 \mu A \) was about \( S_{V,noise} = 6.35 \times 10^{-16} \). Using this value, along with the absolute sensitivity of the sensor at that bias \( S_A = 4.63 \times 10^{-5} \), the detection limit was estimated to be \( B_{DL} \approx 54 \) nT, which is comparable to previously studied measurements of similar systems [10].
High Current Circuit Board Response

Initial measurements of the magnetic fields produced by circuit board traces were performed by biasing a trace with 7 A of current at varying Hall sensor sensitivity levels. The output voltage of the Hall sensor was run through a low-noise preamplifier, which was then connected into an oscilloscope/multimeter system (Figure 23).

While biasing the trace with an equipment maximum of 7 A and measuring the Hall voltage, it was estimated that the produced magnetic field from the trace is about 500 mGauss. This was confirmed with a commercial Lakeshore Hall sensor. Recalling the Hall sensor response tests, the sensors were exposed to magnetic fields as high as 2500 Gauss. It was found that at a DC bias of 7 A is not strong enough. The magnetic field produced by the circuit board trace produced a minimal Hall voltage response, almost on the order of the noise level of the sensor. At this point, it is prudent to discuss relevant steps to move forward and explore the appropriate response of the sensors to circuit board traces running high currents.
Additional equipment capable of supplying more than 7 A, potentially up to 100 A, will be necessary in order to increase the magnetic field produced, but this alone may not be enough to invoke strong sensor response. For example, there may be an area on the board or next to the trace of maximum magnetic flux density, meaning there may be an optimal spot to place the sensor in order to achieve maximum response. Additionally, the idea of using ferromagnetic materials to act as magnetic field concentrators and amplifiers may be investigated [11]. Previous studies have shown that using a ferromagnetic material, such as cobalt, it is possible to “flip” the magnetic field, making it normal to the Hall sensor surface, as well as focus or concentrate the magnetic field to certain points on a Hall sensor [11]. Doing so can provide magnetic field amplification of up to ten times before hitting the sensor active area. Further studies of magnetic field concentration or amplification in order to provide the highest magnetic field possible incident on the sensor will enable these sensors to be more realistically implemented in high current circuit board current sensing applications.
Summary and Conclusion

GaAs/InGaAs/AlGaAs and GaAs/AlGaAs QW Hall sensors grown by MBE were fabricated using a process of optical photolithography, wet chemical etching, and e-beam contact deposition. Optimal contact resistance was achieved by varying annealing conditions and measured by the transmission-line model (TLM) technique. Characteristics of the sensor, such as linearity, absolute sensitivity, supply-current-related sensitivity, and supply-voltage-related sensitivity, were investigated at different biases. The sensors showed linear Hall voltage response to applied magnetic field. The supply-current-related and supply-voltage-related sensitivities were analyzed and exhibited the expected behavior with increasing bias current and bias voltage, respectively. Noise spectra were measured between Hall voltage terminals to determine the different sources of noise in the system. Observing the noise spectrum at varying sensor bias conditions revealed the presence of G-R noise. Additionally, the varying bias conditions displayed the increasing magnitude of $1/f$ noise with increasing bias. This allowed for the calculation of the Hooge parameter for the GaAs/InGaAs/AlGaAs Hall sensor, which was found to be about $\alpha \approx 1.24 \times 10^{-4}$. The measurements of absolute sensitivity and noise allowed us to estimate the detection limit of the micro-Hall sensor to be $B_{DL} = 54$ nT. Initial studies of high current magnetic field response were performed by mounting the Hall sensor on an external circuit board trace. The experiments with trace current on the order of 7A showed that the magnetic field produced by the circuit board is low (~ 500 mGauss), resulting in a Hall voltage response on the order of the noise level of the sensor. Further studies of magnetic field concentration as well as optimal sensor placement are
required in order to increase the Hall voltage response of the sensor.

Additional measures need to be taken in order to maximize Hall Effect sensor effectiveness. This will require further studies of the response of the sensor to higher DC current as well as current pulses of different durations to determine the bandwidth of the sensor. To do this, it may be possible to send current pulses through a solenoid where the produced magnetic field will be directed normal to the Hall sensor surface. Alternative approaches such as the addition of integrated magnetic field concentrators made of soft ferromagnetic material may be necessary. This will allow the magnetic field to be flipped normal to the Hall sensor surface and increase the sensitivity of the sensor. In addition, different material systems, such as GaN/AlGaN and GaN/InGaN, must be explored for operation of these sensors at high temperature environments.
References


