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Characterization of EMR sensors over a temperature range from 4K to 300K

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CHARACTERIZATION OF EMR SENSORS
OVER A TEMPERATURE RANGE FROM 4K TO 300K

A Thesis

Presented to

The Faculty of the Department of Chemical and Materials Engineering
San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Ariadna Kaplan

December 2007

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ABSTRACT

CHARACTERIZATION OF EMR SENSORS OVER A TEMPERATURE RANGE FROM 4K TO 300K

by Ariadna Kaplan

The purpose of this thesis was the characterization of extraordinary magnetoresistance sensors with homogeneous and localized magnetic fields in terms of magnetic field sensitivity. Characterization was at temperatures that extended from 4 K to 300 K and at RT, respectively. Under homogeneous fields, magnetoresistive sensitivity of $26 \Omega/\text{kOe}$ at 130 K with an applied current of $10 \mu\text{A}$ was obtained. The characterization with localized fields was the first experimental study of its type. The localized field was applied by a magnetic probe that swept the device to which a current of $60 \mu\text{A}$ was applied to the device. The magnetoresistive sensitivity obtained was around $16 \Omega/\text{kOe}$, however this effect was believed to be convolved with a capacitive signal. Therefore, further studies on the real effect of the localized field to EMR devices were performed.

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CHAPTER ONE INTRODUCTION

1.1 Objective

The objective of this thesis was to characterize extraordinary magnetoresistance (EMR) sensors over the range of temperatures 4 K – 300 K with magnetic fields of up to 2 kOe. Magnetotransport characterization was based on the voltage change across each device as a function of the applied field, measured in the presence of a small DC current. This voltage change was used to establish the localized and homogeneous field sensitivity of different device geometries. The characteristics of the initial devices was used to guide fabrication efforts so as to maximize the field sensitivity of future generations of sensors. This project work was performed in the facilities and as a research project of Hitachi Global Storage Technologies, San Jose Research Center.

1.2 Background

EMR is one of many examples of a geometry driven phenomenon known collectively as EXX, whereas E refers to extraordinary and XX refers to a variety of phenomena, such as magnetoresistance (MR), piezoconductance (PC) [1, 2] and/or the recently discovered optoconductance (OC) [1, 2]. EXX are extraordinary transport effects that change the conductances of metal-semiconductor hybrid structures (MSHs). EMR is a magnetic effect produced in the presence of a magnetic field, EPC by an applied stress and, EOC by laser radiation [1, 2].

Typical EMR devices are fabricated from a conductive metal (such as Au) and a III-V semiconductor system that includes a layer that works as a quantum well to provide a two-dimensional electron gas (2DEG) (such as InAs or InSb) [3, 4].

Figure 1 shows a sketch of an EMR device, where the width (W) and the length (L) of the 2DEG quantum well, as well as the locations of the current and voltage probes (IVVI or IVIV), are factors that affect the maximum value of MR obtained [4, 5, 6].

Figure 1. Geometric parameters of an EMR device. Design with asymmetric IVIV geometry.

The current is applied to the electrical contacts $I+$ and $I-$, and flows along electric field lines. When a magnetic field is applied perpendicular to the surface of the metal layer (i.e. perpendicular to the page in Figure 2), the current is largely expelled from the metal shunt by the Lorentz force and flows mostly through the semiconductor [3]. In the absence of a magnetic field, the device has a low resistance, and if the field is high the device has a very high resistance [3, 4] because the Lorentz force changes the electrons' trajectories making them go through the semiconductor that has larger resistance than the metal shunt as shown in Figure 2. In fact, the EMR effect increases in a quadratic fashion with respect to the applied field [7, 8] with the leads in the so-called IVVI

geometry (denoting the order of the leads) and increases quasi linearly with respect to applied field in the IVIV geometry [13, 46, 50].

Figure 2. Schematic of EMR current paths when a) a magnetic field is applied and b) when no magnetic field is applied.

EMR field sensors are promising as a nanoscale technology since the MR depends on control of the current within the device and not solely on the distance between the current probes, which may ease some lithographic constraints [6]. EMR is a spin-orbital effect and thus does not require magnetic materials, which may lead to reduced noise characteristics in sensor applications [3, 4].

1.3 Significance

Some of the possible future applications of EMR are in ultrahigh-density data recording, meaning densities of 1Tb/in² and beyond, as well as in industrial field sensors, medical devices, consumer electronics, appliances [3] and, scanning EMR probe microscope (SEMRPM) [7].

EMR is a candidate to follow Giant Magnetoresistance (GMR) and Tunneling Magnetoresistance (TMR) sensors in hard disk drives. Some potential advantages of EMR technology are low magnetic noise and an intrinsic response speed a hundred times faster than that of current sensors [3, 8]. EMR devices have planar geometry, thus they can be located close to the magnetic medium when reading magnetic information. This is important since the magnetic field from the medium decreases exponentially with distance from the media surface [62].

Further, the response of an EMR device is expected to maintain high sensitivity as it is scaled to small dimensions [3, 9]. The primary disadvantage of the EMR technology is that they are fabricated from materials and processes new to the recording industry, making the adoption of EMR expensive for the recording industry [4, 12]. However, with some innovation of the current EMR processing techniques, EMR fabrication promises to become as inexpensive as IC processing is today [13].

Recording heads for hard disk drives have three main components shown in Figure 3: the read sensor, the write transducer, and the media. The devices that were characterized in this project were designed with read sensor applications in mind.

Figure 3. Writer and magnetoresistive reader integrated in a read-write head [15].

The devices used today for read sensors are based on TMR or GMR effects [14]. The write transducer, also called the writer, is a planar electromagnet that provides a high density magnetic flux which is used to write digital data onto a spinning hard disk coated with magnetic media. The slider is a piece of substrate over which the reader and the writer are fabricated. It is designed to “fly” a few nanometers above the spinning disk that supports the media [14]. Read head sensors with this technology (GMR/TMR) can today read from data recorded with an areal density of 200 Gbit/in² and at a rate of 1GHz [8].

Today's sensors are transitioning from “current-in-plane” (CIP) GMR to “current-perpendicular-to-plane” (CPP) TMR, and in coming years the sensor technology will likely reverse to GMR, but this time with CPP. In general, these MR structures have one layer of hard magnetic material that has a fixed direction of magnetization called the “reference layer” (RL) and one layer that is magnetically soft called the “free layer” (FL) in which the direction of magnetization depends on the external field that the device experiences [14].

Figure 4 is a schematic of a CIP GMR sensor with the different magnetic layers separated by a conducting spacing layer. The device resistance reaches its minimum when the magnetizations of the RL and FL are parallel to each other and its maximum when the RL and FL are magnetized antiparallel.

Figure 4. CIP GMR sensor structure showing the magnetic layers and angle between the magnetic layers that determines the MR.

The GMR signal, which correlates with the presence of “0” and “1” written on the magnetic hard disk, is a voltage proportional to the change in resistance that occurs when there is a change in the relative angle of the magnetization of the RL and PL [14].

In these GMR devices, the signal strength depends almost entirely on the intrinsic physical properties of the materials used; the geometry of the device (e.g. aspect ratio) plays only a minor role [3, 7]. By contrast, an EMR signal is strongly dependent on geometric considerations.

The integrated read-write head with any of the MR technologies: GMR, TMR and hopefully soon EMR, are attached to a head arm that is controlled by an actuator as shown in Figure 4d. The medium spins and the reader reads the magnetic fields that are parallel to the reader and translated to voltage changes that are decoded into 1 and 0 and later into the information saved (words, pictures, music, etc).

GMR / TMR sensors require bands of soft magnetic material around the sensor which serve to deflect stray fields from media outside the field of interest. This is largely because there are so many magnetic components (hard bias, pinned layer, etc.) in the vicinity of the sensor free-layer with these technologies. However, there is a reasonable expectation that an EMR sensor will not require any such shielding since there are no magnetic components in the device at all, so there should be no interference from the surrounding media.

The EMR sensor geometry is fundamentally different from the GMR / TMR sensor geometry in that the device is inherently sensitive to fields perpendicular to the wafer plane, thus removing the necessity of preparing an air-bearing surface orthogonal

to the wafer plane. The concept of a 'planar sensor' with simpler processing requirements has been discussed in the industry many times over the years without advancing further, but the EMR sensor may be the innovation, which drives the concept into product.

However, many hurdles will have to be overcome, including making a matching planar writer (which might also be simpler than the current technology), establishing suitable coatings to allow the EMR sensor to be flown without wear damage, and so forth. It is possible that it is most efficient for the EMR sensor and associated on-board signal amplifier to be processed on a III-V semiconductor wafer that is subsequently bonded onto another type of wafer with the writer on it. However, these issues are beyond the scope of this project.

1.3.1 Comparison of EMR, TMR and GMR

Table 1 compares the maximal expected performance of EMR devices and today's technologies (GMR and TMR) as described by Solin. The EMR effect not only has a significant magnetoresistive signal, which is comparable and even higher than that obtained from GMR that, under certain circumstances has comparable signal-to-noise ratio. Thermally induced magnetic noise impedes performance in GMR and TMR sensors built with magnetic materials from achieving higher areal density. EMR does not have magnetic noise and therefore its signal-to-noise ratio can be larger at least in large devices. However, a potential drawback for EMR is that the magnetic field needed to obtain a significant MR value is large perhaps 0.05 T.

Table 1. Comparison of EMR with GMR and TMR [3].

	4-10	100-1,000	30-40	0.01-0.1	0.005-0.05
	> 35	>300	43	<0.001	0.05
	10	~300	29	0.1	0.005
	15	200 estimated	34	0.1	0.001

1.4 Economics of the storage industry

Hard disk drives have been around for more than five decades, with ever higher capacity and smaller geometric factor. They have become indispensable for everyday life. The storage industry has revenues of approximately 60 billion dollars per year, and ships millions of hard drives every month. This industry is very competitive, and the need for higher areal density of information has consistently driven down prices per megabyte of storage. In fact, the number of bits per square inch of disk has increased by 35 percent per year. In 1967, it was possible to have around 50 Kb in a square inch, in 1973 close to 1.7 Mb, in 1981 about 12 Mb, and in 1995, 1100 Mb [16, 17]. However, to continue on this track, a significant challenge to be addressed is to find magnetic field sensors with high signal to noise ratio that are sufficiently small (<100nm). Further, GMR and TMR have the problem that when the size gets smaller, the magnetic noise increases and the noise associated with the spin-polarized current passing through the device also increases. These problems may limit the areal density achievable to only 320 Gb/in² [4, 3].

Thus, EMR sensors, which contain only nonmagnetic components, represent an attractive option for ultra-high-density storage up to a density of 1 Tb/in² [3, 7]. Figure 5 shows how this technology is incorporated into plans for higher areal density disk drives, with EMR sensors forming part of a group of technologies collectively known as “enhanced magnetic disk drive” that will follow GMR and TMR technologies for increasing areal density [18].

Figure 5. Areal density from 1985 to 2015 [18] (printed with permission of Hitachi Global Storage Technologies).

The increase in areal density has made possible the use of disk drives over smaller devices such as mobile phones, digital cameras (storing hundreds of high-resolution images), handheld personal computers (storing thousands of documents or images) and digital audio devices, such as iPods (storing up to 72 hours of audio) [17].

1.5 Environmental, health, and safety issues

The EMR devices were built using standard recording head processes. Resist was stripped with hot N- Methylpyrrolidone (NMP) which should be handled with butyl rubber or FEP Teflon gloves and should be used in a well ventilated area. Contact with skin eyes and clothing must be avoided.

NMP is moderately toxic in all routes of exposures. Dermal exposure is the most probable exposure since NMP has low vapor pressure. If dermal exposure is prolonged, it can cause redness and dermatitis and a good skin cream must be used [19].

CHAPTER TWO LITERATURE REVIEW

2.1 Overview

The purpose of this project was to characterize Extraordinary Magnetoresistance (EMR) devices over the range of temperatures 4 K-300 K with magnetic fields of up to 2kOe. Characterization was based on the voltage change across each device as a function of the applied field, measured in the presence of a small DC current. The change in voltage per unit of field is termed the “field sensitivity”.

This section describes the work to date on the most important factors of EMR device design. As a starting point, the Hall effect, which underpins the EMR effect, is explained. Important parameters of this effect such as Hall mobility and carrier concentration lead us to the need for a modulated 2DEG for EMR devices. Then, the Finite Element Modeling (FEM) performed by Holz *et al.* and Maat *et al.* comparing the EMR response to a localized field for three different current and voltage tab configurations is analyzed. Last, the work performed by Hoener *et al.* on the dependence of EMR on the device aspect ratio, and that of Moeller *et al.* on the influence of frequency, temperature and applied current on the noise level, are examined. Finally, Boone *et al.* is analyzed and these findings are compared with results of Holz *et al.* and Hoener *et al.*.

All EMR work is related to two key papers written by Solin *et al.* in which the concept was introduced and demonstrated. The EMR effect was discovered in circular van der Pauw disks by Solin *et al.* [5] but since these disks are not easy to fabricate on a

nanoscale, Solin *et al.* looked for alternative geometries. Through FEM studies, they obtained a rectangular configuration that was more amenable to fabrication with techniques used in IC processing. In 2002, Zhou *et al.* published a paper in which a rectangular device was demonstrated [4]. The devices that were characterized in this project had that rectangular structure and a modulated 2DEG as Solin *et al.* proposed in 2002 [9].

2.2 Hall Effect in non-magnetic systems

When there is an applied magnetic field in a conducting or semiconducting material perpendicular to an electric field, E_x (that drives a current, J_x), an orthogonal field to both E_x and the magnetic field B_z , exists and is called Hall field, E_H . A voltage measurement as shown in Figure 6 gives what is called the Hall Voltage, V_H , which is caused by a downward force that all moving electrons experience. This force is called the Lorentz force and is defined by Equation 1, where F is the force acting on a charge moving with velocity v when a perpendicular magnetic field B_z is applied. For an n-type semiconductor $q = -e$ and thus v is in the $-x$ direction [20].

$$F = qv \times B$$

Equation 1

Figure 6. Schematic of the Hall effect.

When a steady state is reached, there is a force eE_H that is balanced with the Lorentz force $e v_x B_z$. The current density, J_x , is defined by $e n v_x$, as shown in Equation 2. Therefore, if we define the Hall coefficient, R_H , given in Equation 3, and we apply the definition of conductivity for an n-type semiconductor (given in Equation 4), the Hall mobility, μ_d , can be defined as the product of R_H and σ , where σ is the inverse of the zero-field resistivity, ρ (Equation 5) [20].

$$e v_x B_z = e E_H = \left(\frac{1}{n} \right) J_x B_z \quad \text{Equation 2}$$

$$R_H = \frac{E_H}{J_x B_z} = \left(\frac{1}{en} \right) \quad \text{Equation 3}$$

$$\sigma = en \mu_d \quad \text{Equation 4}$$

$$\mu_d = -R_H \sigma = -\frac{R_H}{\rho} \quad \text{Equation 5}$$

The Hall coefficient, R_H , is a measure of the Hall field; the larger R_H , the larger is E_H per unit of current and field. For semiconductors, R_H is positive and greater than in metals (most metals have large negative values). Hall mobilities for semiconductors are also greater which make them the best candidates for the Hall effect. Semiconductors with the highest values of mobility are InSb and InAs that have values of $8 \times 10^4 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ and $3.3 \times 10^4 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ at $T = 300 \text{ K}$, respectively [20].

Boero *et al.* studying performance, technologies and applications of Micro-Hall devices compared different materials as Bi, GaAs, Si, InSb and different types of semiconductor composites. Bi has been shown to have magnetic field sensitivity with values around $70,000 \text{ nT}/\sqrt{\text{Hz}}$ whereas InSb had much better values of about $4 \text{ nT}/\sqrt{\text{Hz}}$. It is worth noting that these values were obtained from different device sizes and currents and are based on Hall cross-sensors as the main application and geometry [21]. Mishima *et al.* and Zhang *et al.* studied the structural defects of InSb/ $\text{Al}_x\text{In}_{1-x}\text{Sb}$ grown on GaAs and found that micro twins diminished the mobility as the connecting layer was moved closer to the interface [22, 23]. However, Solin *et al.* chose an InSb composite as the preferred material to build the first rectangular EMR device even though it had a Schotky barrier at the Au/InSb interface, reducing the EMR signal [8]. Later publications studied EMR devices using InAs as the 2DEG with Ohmic contacts with Au [9, 13] as well as EMR devices based on Si [10].

2.3 EMR a geometrical magnetoresistive effect

The description of the Hall effect in section 2.2 assumes an infinitely long bar. If the width of the semiconductor bar is close to the length, then the Hall voltage is not well described by Equations 2, 3, 4 and, 5. In this event, the Lorentz force cannot be balanced by eE_H making electrons deviate from the least resistance trajectory. This variation in resistance with the bar geometry is called the geometrical magnetoresistance effect.

Solin *et al.* showed that special geometries could be used to enhance the Hall effect and termed these observations EMR. The original experiments were performed with van der Pauw disk geometry with a metallic inclusion in the center. It was shown that when the metallic inclusion and the contacts at the sides are at the same potential and a current is applied to the outside contact then, if no magnetic field is applied, the current takes the least resistance trajectory and would pass through the center inclusion before exiting the device. However, if a finite magnetic field is applied, the current is forced to take a higher resistance trajectory that is through the whole semiconductor. An illustration of the least resistance trajectory and the higher resistance trajectory is shown in Figure 7.

Figure 7. EMR in a modified Van der Pauw disk with: a) zero-field trajectory and b) finite field trajectory.

Solin *et al.* studied the variations of the non local resistance, R_v , measured as the voltage difference of the two metal contacts not carrying current divided by the current carried by the current leads at room temperature as a function of the ratio of the radius of the metal inclusion, r_a , and the radius of the semiconductor, r_b . They found that the resistance increases as the ratio $\alpha = r_a/r_b$ decreases. In fact, the largest resistance was found for the semiconductor disk without metallic inclusion (open square). Figure 8a illustrates the variation of resistance with the r_a/r_b ratio when a magnetic field of 1 T is applied. Solin *et al.* defined the magnetoresistance, MR, as the percent variation of the resistance when a magnetic field was applied, $R(B)$, and when there is no magnetic field, $R(0)$ as indicated in Equation 6a and b. R_{vv} in Equation 6b is defined by Equation 6a.

$$R_{vv}[B] = \frac{V_1(B) - V_2(B)}{I(0)} \quad \text{Equation 6a}$$

$$MR [\%] = \frac{R_{vv}(B) - R_{vv}(0)}{R_{vv}(0)} \cdot 100 \quad \text{Equation 6b}$$

Figure 8b illustrates the MR for different α values. The highest MR is obtained when the center inclusion has a ratio of 13/16 (closed circles) however, for ratios of 14/16 and 15/16 the MR saturates at a field around 2 T because there is not much space in the semiconductor for accumulation of charge. When the applied magnetic field is lower than 2 T the MR increases with the radius of the metal disk because the trajectory of electrons is larger since electrons are confined to a larger perimeter [8]. Note that this definition of magnetoresistance normalizes the signal with the non-local resistance at zero magnetic field, which will depend on geometry. It is not the definition most closely connected to signal or signal to noise.

This effect in a metal-semiconductor was studied before by Weiss. He observed a large MR in NiSb/InSb structure [24]. However, the type of van der Pauw structure Weiss used was used before by Wolfe *et al.* [25] to study the dependance of mobility and Hall coefficient in an inhomogeneous semiconductor. Figure 9 shows the van der Pauw, the Corbino and the circular EMR structures [26].

Figure 8. EMR effect in a device with Corbino geometry of InSb and Au at room-temperature. a) resistance up to 1T and b) high field MR for different values of $\alpha = r_a/r_b$ where, $16\alpha = 0, \square; 6, \blacksquare; 8, \blacktriangledown; 10, \triangle; 11, \blacktriangle; 12, \circ; 13, \bullet; 14, \diamond$, and $15, \blacklozenge$. From [Solín et al., SCIENCE 289: 1530-1532 (September 2000)]. Reprinted with permission from AAAS.

Figure 9. Sample geometries: a) van der Pauw, b) Corbino and, c) circular EMR [26].

Poplavskyy observed also that the magnetoresistance in semiconductor-metal composite van der Pauw disks depends mainly on the radius of the metallic disk [27]. The EMR devices with a circular configuration used to demonstrate the EMR effect showed to be difficult to build with the standard semiconductor processing. Therefore, Zhou *et al.* used bilinear conforming mapping to unfold this circular geometry of the first

EMR devices obtaining a rectangular structure that was easier to fabricate. Figure 10 shows the new semiconductor-metal layered structure that was more amenable for applications in mesoscopic sizes. With this new geometry Zhou *et al.* obtained MR values of 550% at 0.05T for a width to length ratio of 1/21 [4].

Figure 10. Unfolding of a circular EMR device.

They found that the width to length ratio was an important factor and played the role of the ratio α of the first circular EMR device demonstrated by Solin *et al.* in 2000. Zhou *et al.* measured the MR response for two IVVI configurations (meaning I the current lead and V the voltage lead), the asymmetric and the symmetric configuration, obtaining the highest response in the asymmetric configuration [4].

In 2002, Solin *et al.* published the design of a EMR device that had the geometry shown in Figure 11 with a semiconductor layer that was called a Modulated Two-Dimensional Electron Gas or modulated 2DEG that proved to improve the MR signal because of lowest carrier density for the highest Hall mobility.

The new rectangular geometry, was easier to fabricate than circular geometries. However, it still required not traditional (semiconductor) processing steps such as, multistep electron-beam with angled depositions and shadow masking techniques [13].

In 2003, Solin *et al.* published results of experiments on EMR devices with the same rectangular shape and a modulated 2DEG on InSb. They obtained EMR of 35% with an applied field of 0.05 T and dimensions of 35 nm long, 30 nm wide and 20 nm high [28]. They compared their results with those obtained in a Te-doped InSb thin film circular EMR device and observed that the EMR obtained in the rectangular devices is lower than that obtained in the circular devices under identical conditions. In fact, they obtained EMR of 700 % [29]. Solin *et al.* regard this difference as a residual current leakage through the quantum well lower barrier (mesa floor) [28, 30] and a mobility difference of 1.9 ($\mu_{\text{circular}} = 4.5 \times 10^4 \text{ cm}^2/\text{Vs}$, $\mu_{\text{rectangular}} = 2.3 \times 10^4 \text{ cm}^2/\text{Vs}$, and $\mu_{\text{circular}}/\mu_{\text{rectangular}} = 1.9$).

Figure 11. SEM of rectangular EMR device with Modulated 2DEG. Reprinted with permission from [APL **80**, 4012-4014]. Copyright [2002], American Institute of Physics.

2.4 EMR sensitivity

The two-dimensional electron gas is a semiconductor that provides high-mobility carriers which are constrained to move in a two dimensional plane within a

semiconductor heterostructure. The applied field (B), the mobility (μ) and the carrier concentration (n) in the 2DEG affect the resistance, R_{vv} , of an EMR device as shown in Equations 7, 8 and, 9 where, T is temperature and ρ is the zero-field resistivity [20, 8]. EMR depends quadratically on mobility for the IVVI geometry and proportionally to the mobility for the IVIV geometry thus a high mobility is needed to obtain the highest EMR signal. R_o and R_o' are geometrical constants that affect the total resistance and μ_o is the mobility of carriers for $T = 0$ K. In a doped non-hybrid semiconductor, at high carrier concentration the mobility drops because of a higher number of collisions among carriers. In EMR a high carrier concentration for the lowest zero-field resistance is a requirement, as seen from Equation 9, where ρ is inversely proportional to the carrier concentration.

$$R_{vv}=R_o+ \Delta R [\mu B]^2 \quad (\text{IVVI geometry}) \quad \text{Equation 7a}$$

$$R_{vv} =R_o' +\Delta R [\mu B] \quad (\text{IVIV geometry}) \quad \text{Equation 7b}$$

$$\mu = \mu_o - A [T^{3/2} / n] \quad (\text{non-hybrid semic}) \quad \text{Equation 8}$$

$$R_{ii}(B=0) = \rho \propto \frac{1}{n} \quad \text{Equation 9}$$

To obtain a high carrier concentration and a high mobility, 2DEGs was engineered as a “composite” of different semiconductor layers then called a “Modulated 2DEG” [31, 32] heterostructure. The Modulated 2DEG was proposed by English *et al.* [31]. They proposed a GaAs structure that reached low temperature electron mobility of $5 \times 10^6 \text{ cm}^2/\text{Vs}$. The properties of such a film were explained by Stormer and Tsui [33],

and this work was awarded the Nobel prize in 1999 [34]. The modulated 2DEG structure used in the devices characterized in this project is shown in Table 2.

Table 2. Modulated 2DEG used in the EMR devices to be characterized in this project (Printed with permission of HGST).

#	Layer	Thickness [Å]	Material	Sheet Charge [cm ⁻²]	Temp. [°C]
0	Substrate		GaAs	-	-
1	Buffer	1,000	GaAs	-	570
2	Buffer	50	AlAs	-	570
3	Buffer	300	AlAs	-	570
4	Buffer	10,000	Al _{0.8} Ga _{0.2} Sb	-	530
5	Lower liner	20	AlSb	-	570
6	Channel	125	InAs	5e11	500
7	Upper liner	20	AlSb	-	500
8	Upper barrier	140	Al _{0.8} Ga _{0.2} Sb	-	500
9	Cap	40	InAs	-	500

The 2DEG “channel” (layer 6) used in the devices described here is a semiconductor that is as close as possible to a pure crystal with no doping, dislocations or any type of imperfection that would introduce stress-strain fields to the material which would lower the mobility of the carriers. The upper and lower liners along with the upper barrier and lower barrier are the source of carriers. Carriers from the two Al_{0.8}Ga_{0.2}Sb layers tunnel through the AlSb layers to the InAs pure crystal and form a 2DEG in the InAs channel which has high carrier concentration and high carrier mobility.

The cap layer of InAs (layer 9 in Table 2) provides a corrosion barrier to protect the underlying layers from oxidation. In addition, the InAs cap makes possible to make a direct Ohmic contact to the 2DEG via direct metal deposition (which is helpful for

making test devices) because the Fermi energy of InAs is pinned above the bottom of the conduction band [36, 37]. In an EMR device the current is applied through one metal contact and electrons in the metal that are more energetic than those in the conduction band of InAs are tunneled into the semiconductor cap [37, 38]. Electrons flow into the 2DEG and are drained through a second contact; the non-local voltage is measured through similar contacts located elsewhere on the device.

2.5 Spacing loss and proximity to the magnetic media

In magnetic recording, magnetic fields decrease exponentially with distance from the media surface therefore, the closer the source of magnetic field is to a field sensor, the larger the measured signal [13, 14]. Today's magnetic read sensors are flown at around 10 nm above the surface of the spinning media disk [14], and this separation between the sensor and the media leads to a loss of signal (compared to being position adjacent to the media) termed the 'spacing loss'.

To create a deep quantum well for the field-sensitive 2DEG layer within an EMR sensor device, several capping layers are required. This will necessarily contribute to the spacing loss in recording applications, and hence should be of minimal thickness, while serving to maintain the shape and depth of the quantum well, as well as maximizing the mobility. This goal may pose material challenges for the application of EMR for recording and is only just starting to be investigated.

For example, in the materials studied here, the carriers are donated by the surface layer, and thinning the cap layer may increase the carrier concentration due to enhanced

tunneling across the top quantum well barrier, therefore decreasing the mobility of electrons in the 2DEG channel and decreasing the EMR signal [33].

2.6 Mean free path of an electron

In solids and at room temperature, electrons move in a zig-zag fashion, from scattering event to scattering event, called diffusive motion. The average distance traveled by an electron between collisions is called the mean free path (mfp) and is defined by Equation 10, where $\hbar$ is Plank's constant, μ is the electron Hall mobility, n_s is the 2DEG sheet carrier concentration, and e is the electron charge. When the size of a device is smaller than the mfp then on average, electrons move in a straight line [39]. This kind of motion is called ballistic motion and is illustrated in Figure 12. The device's dimension that is smaller or close to the electron's mfp is called "critical dimension". If the device's dimensions were smaller than the critical dimension then the electron motion would be purely ballistic.

$$\text{mfp} = \frac{\hbar \cdot \mu \sqrt{2 \cdot \pi \cdot n_s}}{|e|} \quad \text{Equation 10}$$

Because mfp depends on the Hall mobility, μ , and μ increases as the temperature decreases, the mfp increases with decreasing temperature. As an example, at room temperature, μ and mfp in an InSb quantum well [40] are 7800 cm²/Vs and 0.13 μm respectively, but at 1.5 K μ is 1.1x10⁵ cm²/Vs and mfp is 0.85 μm . Therefore, studying

devices at low temperature allows access to the ballistic regime in larger devices than at room temperature.

Figure 12. Electron trajectories for a) diffusive motion (mfp a lot smaller than device size) and b) ballistic motion (mfp larger or close to device critical dimension).

2.7 Importance of EMR device aspect ratio

Zhou *et al.*, using bilinear conformal mapping, modeled the metal/semiconductor layered structure and concluded that the width to length ratio is an important factor for optimum MR value [4]. Based on their work Hoener *et al.* studied the EMR effect in experimental heterostructures of polycrystalline Au and InAs as a function of the width-to-length ratio (W/L), the Hall mobility and the carrier concentration in the 2DEG, with different specific interface resistivities, ρ_c [41].

The Hoener *et al.* experiments were performed in an IVVI device configuration at 4.2 K and in magnetic fields up to 10 kOe. They found that at $W/L = 0.05$ for 500 Oe and $W/L = 0.035$ for 10 kOe the EMR effect has its maximum and that the highest MR is achieved at $B = 10$ kOe with an interface resistivity of $\rho_c = 10^{-8} \Omega\text{cm}^2$ [41]. These devices were large; the 2DEG length and width were always larger than $200 \mu\text{m}$ and $10 \mu\text{m}$, respectively. The width was larger than the mfp at all temperatures thus, the carriers' motion was at all times diffusive scattering and not ballistic. The device voltage variation was measured in a symmetric lead configuration shown in Figure 13, injecting a current of $1 \mu\text{A}$ into contacts 1 and 5 and measuring voltage across 2 and 4.

Figure 13. Au/InAs (2DEG) hybrid configuration.

They observed that in a device at 4.2K, with $W/L = 0.035$ and a zero field resistance of $R_0 = 30\Omega$, the MR is 20 % for a field of 10 kOe [41]. The magnetoresistance was measured for different widths and lengths, and they were able to conclude that the ratio W/L is important to the MR value but not the absolute width or length at least in the diffusive transport regime. In fact, Hoener *et al.* were able to show with these experiments that the MR value increases inversely with the W/L ratio [41]. The smaller the W/L ratio, the larger the increase in resistance from zero field to a finite field.

2.8 Importance of the contact interface resistivity

The optimum MR curve has the lowest zero-field resistivity. Thus, contact resistivity has a large effect on the MR value as well as on signal to noise ratio. In a hybrid structure such as the one shown in Figure 7, if there is no magnetic field, the current will take the least resistance trajectory. This trajectory will be through the metal if the contact resistance and the resistance of the metal combined are not larger than the resistance of the current going through the semiconductor. Otherwise, the current trajectory at zero magnetic field will not be different than the current trajectory at a certain finite low magnetic field. The influence of contact resistivity on EMR was studied and characterized by Hoener *et al.*.

Hoener *et al.* had experimentally shown that ρ_c should have the smallest possible value to maximize EMR. Devices with specific interface resistivity below $\rho_c = 2 \times 10^{-8} \Omega\text{cm}^2$ have larger EMR than devices with higher ρ_c . In fact, MR_a values of about 1,000% were found with $\rho_c = 10^{-8} \Omega\text{cm}^2$ and W/L less than 0.05 [41]. Note that this excessively large value is due mostly to the low value of R_{vv} ($B=0$), which can be adjusted arbitrarily by geometry. Nevertheless, this large value implies a large signal as well. When the interface resistance is low the current applied to the 2DEG is shunted more effectively by the metal film and therefore R_0 is lower and the MR (10 kOe) is higher. Möller *et al.* [42] experiments agreed with Hoener *et al.* results and Holz *et al.* confirmed their findings using Finite Element Modeling (FEM) [43, 44].

2.9 Finite element modeling and guidance for lead positioning

Moussa *et al.* and Holz *et al.* have modeled the magnetoresistive response of an EMR device to a localized magnetic field using Finite Element Modeling (FEM) [43, 45]. Maat *et al.* and Boone *et al.* have selected the best configuration of the voltage and current probes for the highest voltage signal [13, 46].

Holz *et al.* have studied the magnetoresistance of an EMR device for different probe configurations and different positions of a localized inhomogeneous magnetic field. They worked on a device such as the one shown in Figure 6, with a 2DEG width to length ratio (W/L) of 0.021, a mobility (μ) of $70,000 \text{ cm}^2(\text{Vs})^{-1}$, a carrier concentration (n) of about $5 \times 10^{11} \text{ cm}^{-2}$, a contact resistivity at the semiconductor-metal interface (ρ_c) of perhaps as low as $2 \times 10^{-8} \Omega \text{ cm}^2$, a tab width (Δ) of 950 nm and an I+ tab to I- tab length ($2d$) of 8600 nm. The 2DEG was built on InSb [6].

They compared three IV configurations by measuring the magnetoresistance when a magnetic dot, simulating the field from a magnetic bit in a recording application, as shown in Figure 14, is at different locations. The magnetoresistance was calculated following Equation 11 [6]. In Equation 11, MR_{dot} is the magnetoresistance, calculated as the difference of the resistances defined by $R_{13} = V/I$, where I is an applied DC current and V the voltage measured, calculated when the localized field sweeps from $B_{i,\text{dot}}$ to $B_{f,\text{dot}}$ with subscripts i and f standing for initial and final field respectively.

$$MR_{\text{dot}} = 100 \cdot [R_{13}(B_{f,\text{dot}}) - R_{13}(B_{i,\text{dot}})] / R_{13}(0) \quad \text{Equation 11}$$

Figure 14. Holz modeled geometry. Reprinted with permission from [APL **87**, 072513]. Copyright [2005], American Institute of Physics.

Figure 15 shows calculated MR_{dot} at different dot positions for different lead positions with a magnetic field that sweeps from +50 mT to -50 mT. In the symmetric IVVI configuration the $MR_{\text{dot}} > 0$ if it is between voltage lead, V_3 and right current lead (between locations a and d), reaching an absolute maximum value of $MR_{\text{dot}} \approx 9\%$ at two symmetric positions between V_1 and the left current probe and V_3 and the right current probe. In the asymmetric IVVI configuration MR_{dot} reaches a maximum only at one location with $MR_{\text{dot}} \approx 18\%$. In the IVIV configuration the MR_{dot} is 18% between the right current lead and V_4 and in locations to the left of the right current lead the MR_{dot} drops quickly to zero which means that the sensor is relatively insensitive to neighboring bits, i.e. it is “self-shielding”.

Figure 15. $MR_{\dot{d}ot}$ at different locations of the EMR device.

Holz *et al.* concluded that the $MR_{\dot{d}ot}$ values depend crucially on the distance between the voltage lead, V_3 , and the right current lead and suggested that the $MR_{\dot{d}ot}$ will increase if the distance between V_3 and the right current probe is confined to a very small area [6, 47].

An important point from the Holz *et al.* work is that the location of the highest sensitivity depends more on the separation between the voltage and the current probes than on the magnitude of the localized magnetic field [6, 48]. Figure 16 shows $MR_{\dot{d}ot}^\circ$, defined by Equation 11 with $B_{i,\dot{d}ot} = 0$, as a function of the localized magnetic field for the three IV configurations and four different dot locations.

The response of the device to a localized field ranging from -50 mT to 50 mT is almost a mirror anti-symmetric about zero field however for a given non-zero field there is a striking dependence of $MR_{\dot{d}ot}^\circ$ on the IV probe distance in the IVIV configuration and the VI probe distance in the case of IVVI configuration and, as well as on the dot location [6].

Figure 16. $MR^0_{\dot{B}}$ as a function of $B_{\dot{B}}$ for four different locations and three different configurations: a) symmetric IVVI, b) asymmetric IVVI and, c) IVIV. Reprinted with permission from [APL 87, 072513]. Copyright [2005], American Institute of Physics.

Holz *et al.* compared the localized field sensitivity calculations with those obtained in their previous work [48, 49] for an homogeneous field applied to the same device geometries. Their earlier findings are shown in Figure 17. MR^0 is defined by Equation 12, where R is the resistance measured the magnetic fields, B_i , B_f or B_0 where the subscripts indicate initial, final or zero magnetic field respectively. With a homogeneous field, the highest sensitivity is found in the asymmetric IVVI geometry, with a maximum $MR=134\%$. That is, the MR in a homogeneous field is seven times that of

the MR in an inhomogeneous field even though the dot covers just 1/60 of the semiconductor area. This implies that the MR does not scale linearly with the dot size. Accordingly, Holz *et al.* hypothesize that the IV distance does not necessarily need to decrease to be able to read smaller bits, a possible advantage of EMR sensors [6].

$$MR = 100 \cdot [R(B_f) - R(B_i)] / R(0)$$

Equation 12

Figure 17. MR^0_{hom} for three IV configurations: symmetric IVVI (V1-V3), asymmetric IVVI (V2-V3) and IVIV (V3-V4). Reprinted with permission from [APL **83**, 16]. Copyright [2003], American Institute of Physics.

Maat *et al.* [46] used FEM to show that, in a model like the one in Figure 6, using a constant current source, the IVIV configuration has a large MR value, has a localized sensitivity much smaller than the device size and that the magnetoresistive response varies in a linear fashion with the magnetic field as was also shown by Holz *et al.* [48] and Moussa *et al.* [52]. In fact, Figure 18 shows Holz *et al.* findings comparing the magnetic field dependence of the MR for the IVVI configuration and the IVIV configuration.

Figure 18. MR response for the a) IVVI configuration, b) IVIV configuration, and c) sketch of the semiconductor-metal hybrid structure. Reprinted with permission from [APL 86, 072513]. Copyright [2005], American Institute of Physics.

The linear MR response of the IVIV configuration is compared with the IVVI configuration that shows non-linear-parabolic MR with respect to the applied magnetic field [48]. Maat *et al.* [46] showed that the magnetic bit will be read by the sensor if it is in between and close to the voltage tabs. Therefore, the minimum photolithographic feature is very important for defining bit resolution [46], and may limit the scalability of EMR devices to nanometer dimensions. Maat *et al.* also proved with modelling that for VIV tabs located close together the magnetic bit resolution depends on the voltage tab

separation rather than in the current-voltage tab distance which was what Holz *et al.* found for leads with larger spacing [13, 46].

Maat *et al.* [46] modeled the potential difference along the lower edge (opposite to the device shunt) as a local field source between zero and 1kOe is moved along the device as shown in Figure 19. This figure shows that the largest voltage change is achieved in between the voltage leads, at the current lead (over the 2DEG) [46]. In Holz *et al.* [6] and in Maat *et al.* [46], the MR response for the IVIV configuration showed that the largest signal at the VIV triad. However, the response is not identical in detail. Maat *et al.* identified fine structure in the response around the voltage leads which Holz *et al.* [6] did not find, likely because Maat *et al.* modeled a more realistic lead structure. Illustration of the modelling by Maat *et al.* modelling is shown in Figure 20.

Figure 19. Potential difference when a localized magnetic field is applied along the lower edge [Maat *et al.*, IEEE Intermag, May 2006].

Figure 20. Three dimensional image of the signal obtained by Maat *et al.* [IEEE Intermag, May 2006].

In the MR definition used by Holz *et al.* [6], given in Equations 11 and 12, the resistance used in the denominator depends critically on the location of the voltage leads and will be very different if the leads are moved a short distance, even though the signal itself will not have changed much. Therefore, Maat *et al.* proposed a new definition of magnetoresistance which is a measure of the signal power compared to the power dissipated in the device, and is thus much more connected to the signal noise ratio, and is more useful in engineering practical devices. Equation 13 defines MR from this perspective. For comparison, Equation 14 gives the definition of MR used by Holz *et al.* in terms of voltage rather than resistance as defined in Equation 11 [46, 6].

This discrepancy in the definition of MR can give values that vary by many orders of magnitude as it is shown in Figure 21. In this figure we see the MR as a function of the applied field at different contact resistances. If for example, we pick the open triangle that corresponds to a contact resistance of $10^{-6} \Omega \text{cm}^2$, the MR_1 is $10^2 \%$ at $H = 0.5 \text{ kOe}$ while the MR_2 is $10^{-2} \%$ at 0.5 kOe , a difference of $10^4\%$. Note here that the Maat *et al.* definition conforms the industry standard for data recording sensors, and hence will be the definition used in this work.

Definition of MR used by Maat *et al.*:

$$\text{MR}_2(\%) = 100 \bullet \frac{(V^+(H) - V^-(H)) - (V^+(H=0) - V^-(H=0))}{(V_{I^+}(H=0) - V_{I^-}(H=0))} \quad \text{Equation 13}$$

Definition of MR used by Holz *et al.*:

$$\text{MR}_1(\%) = 100 \bullet \frac{(V^+(H) - V^-(H)) - (V^+(H=0) - V^-(H=0))}{(V^+(H=0) - V^-(H=0))} \quad \text{Equation 14}$$

Based on an optimum configuration obtained through the FEM work of Maat *et al.*, Boone *et al.* built and characterized EMR devices and tested them with a bias current of $100 \mu\text{A}$ and a field sweep from zero to $\pm 320 \text{ Oe}$. The largest signal sensitivity obtained by Maat *et al.*, $5 \mu\text{V/Oe}$ agrees with the signal obtained from FEM assuming a 2DEG sheet resistance of $400 \Omega/\text{sq.}$, μ of $15,100 \text{ cm}^2/\text{Vs}$ and a ρ_{contact} of $2.6 \times 10^{-7} \Omega \text{ cm}^2$, which was in agreement with the values of the characterized devices [13, 46]. This signal amplitude is comparable to the signal obtained from GMR sensors.

Figure 21. Finite Element Modeling displayed using the two definitions of magnetoresistance MR_1 and MR_2 [Maat *et al.*, IEEE Intermag, May 2006].

Moussa *et al.* modeled the sensitivity to a local magnetic field in van der Pauw and rectangular devices using FEM also, but using the MR_1 definition of magnetoresistance. In the rectangular devices they studied the MR response of devices with IVVI and IVIV geometry [45, 52]. Interestingly, Moussa *et al.* obtained in the IVIV geometry a similar pattern as Maat *et al.*. But Moussa *et al.* found that at in the I lead of the VIV triad, there is a big drop in the magnetoresistive signal. In further contrast with Maat *et al.*, Moussa *et al.* did not show two smaller signal drops for the voltage leads.

This is likely to a combination of differences introduced by the MR_1 definition of magnetoresistance and the way the leads were modeled in the two papers (Maat *et al.* includes the actual lead tab geometry). Unfortunately, as in the case of the Holtz *et al.* study, the value of the signal cannot be derived from the paper, and therefore cannot be directly compared with the signal derived by Maat *et al.*. Figure 22 shows the results of the modeling performed by Moussa *et al.* in rectangular EMR devices.

Figure 22. MR response of the VIVI configuration to a localized field at different locations of the magnetic bit with a magnetic field of 500 Oe. The leads are 20 nm thick and their location is represented with the black squares in the x-axis. Center leads and side leads are separated 60 nm and 300 nm, respectively. Reprinted with permission from [J. Appl. Phys **94**, 2 1110-1114]. Copyright [2003], American Institute of Physics.

2.10 Size and the diffusive to ballistic transport transition

The signal obtained by Boone *et al.* in micron size devices is comparable with GMR/TMR sensors, whose signal does not change much with size down to dimensions of 100 nm [13], in part because the mean free path of carriers is only a few nm in metals. Even though the eventual use of the device will be to detect localized fields, the excitations by external homogeneous magnetic fields can be used to predict the behavior

of the local response [13]. Note that for magnetic recording applications, voltage tab separations similar to those of the data trackwidth (<100 nm) on the hard disk will be required, and the response may be different at small sizes, as described next [13].

The critical dimensions of these future EMR devices, specifically the lead dimensions, will necessarily be smaller than the room temperature mean free path (mfp) of the carriers in the 2DEG defined by Equation 10. Accordingly, the nature of the electron transport is expected to include ballistic behavior. When there is ballistic transport the Hall effect is reduced [13] but it is not yet known what behavior the EMR effect will exhibit in the ballistic regime. At room temperature, carriers in the 2DEG, such as the one described in Table 2, have mfp around 200 to 300 nm. Some of the devices measured here have tabs separated by less than 100nm.

In the EMR devices characterized by Boone *et al.*, n_s ($5 \times 10^{11} \text{ cm}^{-2}$) is relatively independent of temperature, however the Hall mobility is strongly dependent on temperature. For instance, it increases from $7,000 \text{ cm}^2/\text{V.s}$ at 300 K to $28,000 \text{ cm}^2/\text{V.s}$ at temperatures below 50 K, thus the mfp is 80 nm at 300 K and 325 nm at 5 K. Figure 23 shows transfer curves obtained from an IVIV geometry device with an applied current of $10 \text{ }\mu\text{A}$. It is observed that the resistance increases slightly as the temperature decreases. Figure 12a also shows a non-linear transfer curve at 5 kOe which Boone *et al.* hypothesize that may be caused by the cyclotron effect [13].

Figure 23. Temperature dependence of the EMR. Comparison of MR measurements at a) 5 K and 300 K and b) ranging from 100 K to 300 K [Boone *et al.*, IEEE Trans. Magn. **42**, 10 1-3, 2006].

2.11 Noise and geometry studies

Möller *et al.* reported noise measurements in Au-InAs hybrid structures. Their findings are important because the magnetic field sensitivity of any MR sensor is determined by the signal noise level. The signal noise level of a GMR or TMR sensor has two major components, the magnetic noise and the voltage noise [53]. The magnetic noise arises from the thermal fluctuations of the magnetic spins in the device and causes resistance (voltage) fluctuations. The voltage noise includes the white noise, also called Johnson noise. One of the primary features of the EMR sensor is that there is no magnetic noise since the device is based on a semiconductor/metal structure with all non-magnetic materials. However, the Johnson noise is still present and may be large due to the generally larger resistance of the device.

The Johnson noise is calculated from Equation 4, where k_B is the Boltzmann constant, T is the temperature and R is the resistance. Equation 15 describes the Johnson noise as only dependent on temperature and resistance [53].

$$\text{Johnson voltage noise} = \sqrt{S_{V,J}} = \sqrt{4k_B T R} \quad \text{Equation 15}$$

Möller *et al.* explored EMR as a function of frequency, temperature and I_{bias} . They found that the Johnson noise is frequency independent above 140 Hz at 4.2 K and above 400 Hz at room temperature [53]. Their experiment has shown that at a field of 10 kOe at room temperature, the noise is near the calculated Johnson noise but at 4.2 K the noise level is higher than the calculated Johnson noise suggesting that in smaller structures the noise level will be higher. Figure 24 shows the dependency of the voltage noise, $S_v^{0.5}$, of an EMR device (with structure shown in the inset of Figure 20a) on the frequency of operation of the sensor [53].

EMR devices are not affected by magnetic noise and thus the scalability is not limited by magnetic fluctuations of the spins but by photolithography on the nanoscale. Möller *et al.* based their experiments on four device sizes (different W/L ratios) and three temperatures (300 K, 77 K and 4.2 K). They found that for samples at 300 K and 77 K the relative discrepancy, defined as the ratio of the experimental and the theoretical Johnson noise ($(S_{v,\text{exp}}/S_{v,j})^{1/2}$), was around 1.5 for frequencies over 1 kHz with a measured resistance of 54.6 Ω [53].

Figure 24. Voltage noise dependence on frequency of the read-head a) at 300K at $I_{\text{bias}}=0$ and $B=0$ and b) at 4.2K with I_{bias} in contacts 1-5 and voltage measured in 2-4. Inset shows the resistance change as a function of B . Reprinted with permission from [APL **84**, 3343-3345]. Copyright [2004], American Institute of Physics.

The white noise level is expected to decrease with decreasing temperature.

Therefore, for a sample at 4.2 K the experimental noise and thus the relative noise discrepancy should be lower. However, the values obtained were larger with a relative discrepancy of 8.6, but Möller *et al.* attributed these results to the noise contributions of the read-out electronics and wiring. They concluded from these experiment that the experimental Johnson noise is not influenced by the area ($W \times L$) [53].

2.12 Summary of literature review

The first section of this chapter explained the basic physics of the EMR effect. The EMR effect is defined as a geometrical magnetoresistive effect, which has been described as a Hall effect in which the Lorentz force was not balanced out because of geometrical constraints. For the IVVI geometry the MR signal depends quadratically in

the product of the applied field times the mobility; for the IVIV geometry the signal is more linear.

The first studies performed in circular EMR devices showed that the ratio α (metal inclusion radius over the semiconductor mesa radius) greatly affects the MR obtained. FEM modeling indicated the equivalency of these circular devices to rectangular devices and related the ratio α with the ratio W/L (width to length ratio). The magnetoresistive response of rectangular EMR devices varies depending on the W/L ratio and shows inverse scalability [41].

The Hall mobility and the carrier concentration are intrinsic factors that affect the MR response. A Hall mobility increment will increase the mfp and the MR signal and a carrier concentration increment will increase the zero-field resistance. Thus, high Hall mobility and low carrier concentration are important for the best MR response of an EMR device. In addition, specific interface resistance should take the smallest value possible since it affects also the zero-field resistance and therefore the finite field MR.

The voltage-lead/current-lead configuration plays an important role in the EMR response. If the voltage leads (V) and the current leads (I) have the IVIV configuration, the resistance versus applied field has a linear response while in the IVVI configuration the response is not linear. Therefore, the IVIV configuration is the most useful for to EMR sensors.

High Hall mobility and low specific contact resistivity are the requirements that determine the selection of the semiconductor. InAs was preferred over InSb based on the fact that InAs/Au contact has a lower specific contact resistivity because InAs makes an

Ohmic contact with Au. InSb, on the other hand, takes a Schottky contact so the specific contact resistivity is larger. For the purpose of this project, the magnetoresistance values of rectangular structures using InAs as a channel along with their intrinsic and geometric characteristics are shown in Table 3.

The definitions used by different researchers varies, therefore the magnitude of the magnetoresistive value cannot be readily compared. Table 3 shows MR values in % and $\mu\text{V}/\text{Oe}$ because of this discrepancy in definitions. The smallest devices studied are those studied by Boone *et al.* and Maat *et al.*.

Table 3. InAs rectangular EMR devices

Authors	MR Model (M) Experiment (E)	T [K] B[Oe]	Rc [$\times 10^{-7} \Omega \text{cm}^2$]	μ cm^2/Vs	n. [$\times 10^{11} \text{cm}^{-2}$]	W/L [$\mu\text{m}/\mu\text{m}$]
Holz <i>et al.</i> IVVI [6]	30% (M)	300K 10kOe	3.5	2.09 T^{-1}	3.5	70/ 200
Boone <i>et al.</i> IVIV [54]	5 $\mu\text{V}/\text{Oe}$ (E)	300K 320Oe	1	7,000 at 300K 28,000 at 50K	5	9/ 0.6
Maat <i>et al.</i> IVIV [46]	2 $\mu\text{V}/\text{Oe}$ (M)	300K 2,000Oe	2.6	15,000	5	9/ 0.6

CHAPTER THREE RESEARCH HYPOTHESIS

The research objective of this project was to characterize EMR devices, in terms of resistance, carrier concentration, sheet resistance, 2DEG depth, device geometry and mobility over the range of temperatures 4 K - 300 K with homogeneous magnetic fields of up to 2kOe. The localized field sensitivity was explored with magnetic sensitivity mapping for the IVIV geometry.

3.1 Assumptions

The devices characterized in this project are rectangular devices with InAs channel that have dimensions $W[\text{nm}]/L[\text{nm}] = 450/9000 = 0.05$ and $W/L = 600/9000 = 0.066$. The devices that are characterized have a 2DEG similar to those devices characterized by Boone *et al.* [54] therefore, it is assumed that at 300 K the mfp is close to 80 nm and at 50 K around 325 nm. Thus, the electron transport was assumed to be diffusive.

It is assumed that the device length was small enough to assure that the EMR effect takes place. Therefore, there is not room for charge accumulation or strengthening of the Hall field.

It is assumed in the localized field sensitivity measurements that the magnetoresistive signal produced by the EMR device is stronger than the capacitive effect between the tip and the sample and that there is no extraordinary piezoconductive effect or EPC (one of the EXX effects) produced by the scanning tip and the sample.

3.2 Hypothesis

Based on the experiments by Boone *et al.* [54] and on the fact that the devices to be characterized have similar dimensions and layer structure. A signal close to $5 \mu\text{V}/\text{Oe}$ for a current of $100 \mu\text{A}$ is expected for an applied homogeneous field.

Based on the modeling by Maat *et al.*, the magnetoresistive signal expected should be maximal near the VIV triad. A large voltage signal beside the I lead (over the 2DEG), accompanied by two smaller peaks beside the V leads, are expected.

CHAPTER FOUR EXPERIMENTAL DETAILS

4.1 Sampling

Characterization of EMR devices was based on measurements of two types of devices, EMR and test devices. EMR devices were characterized with homogeneous and localized fields. With homogeneous fields, the magnetic sensitivity was measured as a function of temperature, and with localized fields, the location of the magnetic sensitivity peaks with respect to the VIV triad as well as the peak intensity was investigated.

Test devices were used for measurements of transport properties of EMR devices such as, sheet resistance (R_s), contact resistance (R_c), Hall mobility (μ), and carrier concentration (n). Two types of test devices were characterized: van der Pauw and TLM (transmission line model) devices. A summary of all the devices measured is given in Table 4.

Table 4. Summary of devices

Field	Wafers	Device	Device Name
Homogeneous	HF	EMR	C10R13, C10R17
		Van der Pauw	HFLvdP200-1, HFLvdP200-2, HFLvdP200-3
		TLM	W5, W10, W20
	HFvdP one device per wafer	Van der Pauw	HFvdP60, HFvdP80, HFvdP90, HFvdP100, HFvdP130, HFvdP160, HFvdP190, HFvdP 200, HFvdP200Av, HFvdP200Bv and HFvdP200C
Localized	LF	EMR	LF1 LF2 LF3 LF4

4.1.1 EMR Devices

Samples were prepared and characterized by collaborators at Hitachi Global Storage Technologies (HGST) using e-beam lithography and standard wafer processing to create arrays of devices in which important parameters such as W/L, voltage lead separations, 2DEG depth, and device geometry were varied systematically.

The device arrays comprise 80 EMR devices along with assorted test devices. EMR devices from two wafers were characterized in this project, HF and LF (H stands for Homogeneous, L for Localized and F for Field). Wafer HF was characterized with homogeneous magnetic fields that were applied using a Lakeshore Desert Cryostat and the response was measured with an Agilent 4155C Parameter Analyzer. Wafer LF was characterized with localized magnetic field measurements, using a Digital Instruments Dimension 3100 scanning probe microscope operated in MSM (Magnetoresistive Sensitivity Mapping) mode.

A standard array of devices is shown in Figure 25 where each column and row contains devices specified in Table 5. In this table, L and W are the length and width of the semiconductor layer, D is the distance between the tabs that was used to apply current and C2C is the center-to-center distance between the voltage tabs as shown in Figure 26. Four devices of wafer LF were wire bonded to a sample holder to perform MSM. The four devices, LF1, LF2, LF3 and LF4, are shown in Figure 27.

Figure 25. Array of EMR devices along with testing devices (μ -TLMs, Van der Pauw devices and Hall Bars) [54] (printed with permission of HGST).

Table 5. Device specifications for wafer HF (printed with permission of HGST).

Tab Design	C2C [nm]	D [μ]	C 10	C 11	C 12	C 13	C 14	C 15
			W [nm], L=9 μ m, W/L=450/9000=0.05, W/L=600/9000=0.066					
Row 11	300	6	600	450	600	450	600	450
Row 12	300	6	600	450	600	450	600	450
Row 13	500	6	600	450	600	450	600	450
Row 14	500	4	600	450	600	450	600	450
Tabless Design	C2C [nm]	D [μ]	W [nm], L=9 μ m, W/L=450/9000=0.05, W/L=600/9000=0.066					
Row 15	300	6	600	450	600	450	600	450
Row 16	300	6	600	450	600	450	600	450
Row 17	500	6	600	450	600	450	600	450
Row 18	300	4	600	450	600	450	600	450

Figure 26. Dimensions of EMR devices in wafer HF (printed with permission of HGST).

Figure 27. Dimensions of devices selected for localized field characterization (printed with permission of HGST).

4.1.2 Test devices

There were test devices in each experimental array, including vdP (van der Pauw) and TLM (Transmission Line Model) devices, as illustrated in Figure 28. They were used to measure the carrier concentration, the mobility of the carriers in the 2DEG, the contact resistivity and the sheet resistance of the device.

4.1.2.1 Transmission line model

The transmission line model was used to determine the contact resistivity of the Au/InAs contacts using the TLM devices, which consisted of a series of metal contacts with a range of different spacings between them, as shown in Figure 28a. The resistance between each pair was plotted as a function of contact separation to obtain a linear relationship. The origin ordinate was equal to twice the contact resistance (R_c) and the slope of the line was the sheet resistance of the semiconductor divided by the width of the TLM device [57]. The contact resistance is inversely proportional to the metal lead width and therefore larger resistance values are expected for the narrower leads. However, because this project is aimed to fulfill the need of the smallest devices possible (with the highest areal density), the width of the leads should be as close as possible to the critical dimension that the lithographic process can achieve, if the R_c is acceptable.

4.1.2.2 Van der Pauw devices

Van der Pauw devices (vdPs) were used to obtain sheet resistance, carrier concentration and Hall mobility of the 2DEG. These devices were created at a range of

length scales, using various types of lithography. Van der Pauw devices may take rather different geometries, as shown in Figures 28b and 29 [57, 58].

Figure 28. Test devices: a) TLM and b) Van der Pauw devices (printed with permission of HGST).

Figure 29. Different geometries of van der Pauw devices: a) cloverleaf and b) square.

4.1.2.3 2DEG depth series characterization

Characterization of the 2DEG properties at different distances from the surface was performed using van der Pauw test devices that had the geometry shown in Figure 29 a and b. These devices were called according to their 2DEG depth, HFvdP60, HFvdP80, HFvdP90, HFvdP100, HFvdP130, HFvdP160, HFvdP190, HFvdP200, HFvdP200Av, HFvdP200Bv, HFvdP200C, HFLvdP200-1, HFLvdP200-2 and HFLvdP200-3 (where HF stands for homogeneous field, L for lithographic and the number at the end is the distance of the 2DEG from the surface).

HFvdP200Av and HFvdP200Bv (v stands for vendor) were devices built and characterized by the wafer vendor from a companion wafer of wafer HF. Therefore, they were supposed to have similar Hall mobilities, carrier concentrations and sheet resistances as device HFvdP200. HFvdP200C was built by HGST from a second companion wafer of HF therefore the transport properties were also expected to be similar to those of HFvdP200.

Measurements on HFvdP200Av and HFvdP200Bv were made to verify that the 2DEG integrity was not compromised by the thinning of the overlayers after processing and that the instrumentation used for transport characterization matched values given by the wafer vendor. Therefore, transport properties in HFvdP200, HFvdP200Av and HFvdP200Bv were expected to be similar to transport properties of lithographic vdP devices built on wafer HF, HFLvdP200-1, HFLvdP200-2 and HFLvdP200-3 if processing did not affect the 2DEG structure.

All the vdP devices (except HFvdP200Av, HFvdP200Bv and the lithographic vdPs) were made at HGST using 7 mm Kapton tape crosses on 10 mm square pieces, with 2 minutes of ion beam etch followed by 50 Å Ta and 2,000 Å Au deposition to create leads on the corners. Figure 30 shows the layered structures of the 2DEG depth series.

Figure 30. Van der Pauw device geometries (printed with permission of HGST).

4.2 Instrumentation

The instrumentation to measure EMR in a homogeneous field comprised of a Lakeshore Desert Cryostat probe station with a vertical superconducting magnet, two temperature controllers (Lakeshore 332 and Lakeshore 340) a Lakeshore 625 power supply for the superconducting magnet, and an Agilent 4155C Semiconductor Parameter Analyzer. The instrumentation to measure test devices was the same as the instrumentation to characterize EMR under homogeneous field, however a Keithley

Source Meter 2400 was used instead of the Agilent 4155C Semiconductor Parameter Analyzer. To perform the MSM measurements a Dimension 3100 scanning probe microscope (SPM) was used. Figure 33 shows the instrumentation for the EMR homogeneous field characterization. Figure 34 shows the Dimension 3100 SPM that was used to perform MSM.

Figure 31. Instrumentation for homogeneous field characterization. Hitachi Global Storage Technologies, San Jose Research Center (printed with permission of HGST).

Figure 32. Instrumentation for MSM. Hitachi Global Storage Technologies, San Jose Research Center (printed with permission of HGST).

Figure 34. MSM experiment (printed with permission of HGST).

4.3 Data analysis technique

The raw data obtained from the Agilent 4155C Semiconductor Parameter Analyzer, Keithley 2400 Source Meter and the Dimension 3100 Scanning Probe Microscope was analyzed using data processing techniques that are discussed in the following subsections.

4.3.1 Transport properties

Van der Pauw devices were characterized following the NIST method [58]. In this method, every corner of the device was labeled with a number, as shown in Figure 35. Voltage measurements with a 1 mA current were used to obtain R_A and R_B . These measurements were performed with the source meter Keithley 2400 in a 4-point probe measurement mode. The sheet resistance was obtained from values of R_A and R_B following calculations given in Appendix A. Mobilities and carrier concentration were obtained with a method similar to that used for sheet resistance. However, in this case

voltage measurements were performed when a positive and a negative magnetic field were applied. Calculations of Hall mobilities and carrier concentrations are shown in Appendix A.

Figure 35. NIST method for characterization of van der Pauw devices.

TLM measurements were performed with the Semiconductor Parameter Analyzer Agilent 4155C. Values of resistance as a function of the distance between contacts (metal/semiconductor) were obtained in units of Ω . The resistance showed a slope of R_s/W with the origin ordinate equal to twice the contact resistance, R_c . TLM measurements were 4-point probe measurements with an applied current of $60 \mu A$.

4.3.2 Homogenous field sensitivity

The voltages across devices of wafer HF were measured while sweeping the field from -2 kOe to 2 kOe while applying a constant direct current of $10\text{ }\mu\text{A}$ and stepping the temperature from 5 K to 300 K . Transfer curves obtained in this manner from devices in wafer HF are given in Appendix B and have the format, $Ax + B$ (where A is the slope in Ω/kOe , x is a variable magnetic field in kOe and B is the origin ordinate in Ω). The slope of each of these transfer curves, A , for each temperature, is typically referred to as the magnetic sensitivity. Examples of transfer curves obtained at different temperatures is illustrated in Figure 36.

Figure 36. Examples of transfer curves obtained at 300K, 250K and 200K (printed with permission of HGST).

4.3.3 Localized field sensitivity

MSM images can be represented in 3D or 2D view. However, for practical reasons, it was easier to work with 2D images. The 2D views given in this thesis represent the voltage signal in terms of color intensity. White is the highest value of the voltage signal and black is the lowest value. The color scale used in all images is shown in Figure 37.

Figure 37. Example of color scale used in MSM images.

The exact value of the voltage signal was obtained using the Dimension 3100 software. A square was drawn surrounding the area with the location of interest and the software returned the maximum, the minimum and the mean of the voltage signal inside the square. An example of the image analysis technique used in this project is shown in Figure 38.

Figure 38. Technique used to analyze MSM images. The green box in the MSM image (left) is the reference box (Ref R). The red box (Box A highlighted in red) surrounds an area that has a depth profile and a bearing area % shown in right plots (printed with permission of HGST).

4.4 Experimental method: measurements and analysis

Measurements in homogeneous fields were performed in high vacuum in a range of temperatures from 5K to 300K on EMR devices that were previously screened in a bench top station, as part of the process shown in Figure 39. Working devices were characterized while sweeping the magnetic field between -2kOe to 2kOe and sweeping the temperature from 5 K to 300 K in steps of 5 K. Also, square macroscopic and lithographic van der Pauw devices as well as TLM devices were measured to characterize

the transport properties of the 2DEG. Four working devices from wafer LF were characterized with a localized field of around 800 Oe.

Figure 39. Experimental steps towards EMR characterization.

CHAPTER FIVE RESULTS AND DISCUSSION

This section summarizes the results of this thesis, organized in three subsections, transport properties verification, homogeneous field and localized field measurements.

5.1 Transport properties verification

Verification of transport properties was based on two types of devices, van der Pauw and TLM devices. Van der Pauw devices of two geometries were used: lithographic cloverleaf and as-grown square. TLMs of three widths were used: 5 μm , 10 μm , 20 μm .

5.1.1 Van der Pauw devices

Table 6 shows measurements of transport properties of the 2DEG depth series. These measurements confirmed that the intrinsic properties were the same before and after processing and that characterization techniques and instrumentation used in this project led to reproducible results since values of mobility, carrier concentration and sheet resistance obtained at HGST matched those obtained by the wafer vendor.

Figure 40 illustrates data given in Table 6 in a convenient form. It shows that the as-grown square vdP, HFvdP200, has a sheet resistance that is very close to that of lithographic vdPs, HFL200-1, HFL200-2 and HFL200-3. Lithographic vdP, HFL200-2, has a sheet resistance that is only 1% (refer to Table 6) larger than vendor's device, HFvdP200Bv. Vendor's device, HFvdP200Av, has a sheet resistance that is 10%

smaller. Hence, processing on the micron size scale did not alter the 2DEG properties and our characterization method is reproducible.

Table 6. Summary of transport properties on the 2DEG depth series.

Name	2DEG depth [Å]	Carrier Concentration [cm^{-2}]	Hall Mobility [$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$]	Sheet resistance (Hall) [$\Omega/\text{sq.}$]
HFvdP200	200	8.89E+11	12342	569
HFL200-1	200	9.37E+11	17300	386
HFL200-2	200	6.66E+11	14874	631
HFL200-3	200	8.51E+11	14800	496
HFvdP200Av	200	6.34E+11	22174	444
HFvdP200Bv	200	5.30E+11	18532	636
HFvdP200C	200	5.18E+11	9539	1262
2DEG depth series - kapton	190	5.19E+11	8956	1342
2DEG depth series - kapton	160	6.90E+11	9448	957
2DEG depth series - kapton	130	8.10E+11	10973	703
2DEG depth series - kapton	100	1.31E+12	11572	412
2DEG depth series - kapton	60	1.29E+12	9622	504
2DEG depth series - kapton	90	1.31E+12	11483	416
2DEG depth series - kapton	80	1.29E+12	11108	435

The values of sheet resistance obtained with the instrumentation and characterization method used at HGST (and in this project) matched values of sheet resistance given by the vendor. The sheet resistance value of the as-grown square vdP built and measured by HGST (HFvdP200) was within the sheet resistance values of the as-grown square vdPs built and measured by the vendor (HFvdP200Av and HFvdP200Bv). Therefore, measurements are reproducible over time and after processing, indicating overall stability of the heterstructure.

However, the sheet resistance of HFvdP200C that was built from the companion wafer of HF was more than twice that obtained in the square vdP built from HF (HFvdP200). These two wafers were expected to have the same transport properties. This large variation in properties was likely because of subtle variations in the growth of the semiconductor heterostructure.

Figure 40. Sheet resistance measured on lithographic and macroscopic vdP devices (printed with permission of HGST).

Figure 41 shows that the carrier concentration decreased by a factor of 3 with increasing distance to the surface. Surprisingly, it was seen in Figure 42 that the Hall mobility did not vary much with distance of the 2DEG to the surface. In fact, it was expected that the increase in carrier concentration would limit the mobility of electrons

leading to a decrease in Hall mobility. However, there was only a shallow peak at a 2DEG depth of 100Å.

Figure 41. Carrier concentration measured on lithographic and macroscopic vdP devices (printed with permission of HGST).

Sumarizing, decreasing the 2DEG depth led to an increase in carrier concentration and a decrease in sheet resistance as was expected from the literature (Section 2.4). A decrease in Hall mobility with the 2DEG depth was expected but a rather shallow curve was obtained. The Hall mobilty did not decrease with 2DEG depth.

Figure 42. Hall mobilities measured on lithographic and macroscopic vdP devices (printed with permission of HGST).

5.1.2 Transmission line method

Transmission line method (TLM) measurements showed that the resistance was linearly dependent on the nominal length of the device. In Figures 43 the linear dependence of resistance versus length has a different slope for different widths (W) of the device (10 μm and 20 μm). The resistance shows a slope of R_s/W (R_s =sheet resistance) with the origin ordinate equal to twice the contact resistance, R_c . Estimates of R_c , and R_s , are given in Table 7. Note that the value of R_s obtained for 20 μm was inside the range of values obtained from lithographic vdPs (380-630) Ω/sq . Values of R_c obtained here ($\sim 1\text{E-}6 \Omega \text{ cm}^2$) were at least four times those obtained by Boone *et al.* [54]

($2.8 \times 10^{-7} \Omega \text{ cm}^2$). These lengths were nominal lengths; values of W or L were not measured using AFM or SEM.

Figure 43. TLM measurements for widths: 10 μm and 20 μm (printed with permission of HGST) .

Table 7. Estimation of specific contact resistivity and sheet resistance based on TLM measurements.

W	$R_s/W x + 2R_c$	$R_c [\Omega \text{cm}^2]$	$R_s [\Omega/\text{sq}]$
10 μm	$86.71x - 322$	$(322/2) \times 10^{-8} = 16.1 \times 10^{-7}$	$86.7 \times 10 = 867$
20 μm	$50.63x - 201.63$	$(202/2) \times 10^{-8} = 10.1 \times 10^{-7}$	$50.63 \times 20 = 506$

5.2 Homogeneous field

Initially, some fraction of the devices in wafer HF was destroyed during measurement because there were grounding problems with the instrumentation. The grounding of the tool was consequently modified, adding ground straps to the Cryostat to minimize the electrostatic potential between investigator and tool.

TEM analysis showed that the extreme sensitivity of the devices to the electrostatic discharge (ESD) events was likely due to a corrosion problem, which caused poor adhesion between metal contacts and the semiconductor heterostructure. TEM data from a previous experiments, showed that Au was getting into the top barriers and that there was corrosion provoking the metal pads to peel off and causing high sensitivity to ESD and low yields. Figure 44 shows the TEM data where the shunt interface with InAs 2DEG is good, but Au has migrated into the AlGaSb top barrier from the shunt.

Figure 44. TEM characterization [59] (printed with permission of HGST).

5.2.1 Measurements

Voltages across devices of wafer HF were measured while sweeping the field from -2 kOe to 2 kOe while applying a constant direct current of $10\text{ }\mu\text{A}$. Measurements were taken at a series of temperatures, which were stepped from 5 K to 300 K . Transfer curves obtained in this manner from devices in wafer HF are given in the Appendix B. Figure 45 shows the data obtained in terms of Ω/kOe as a function of temperature. Note that the signal obtained was around $26\text{ }\Omega/\text{kOe}$, around 5 times what Boone *et al.* [54] obtained ($5\text{ }\Omega/\text{kOe}$ with $100\text{ }\mu\text{A}$) with earlier generation devices of the same geometry.

Figure 45. Dependence of magnetic sensitivity on temperature. Squares and stars show values obtained in devices R17C15 ($W/L=0.05$) and R13C10 ($W/L=0.066$), respectively (printed with permission of HGST).

Figure 45 shows that the dependence of the MR signal on temperature between 4.2 K and 300 K is weak, with a broad maximum around 150 K . This suggests that in

agreement with Boone *et al.* [54], the magnetoresistance increases as temperature decreases for temperatures over 150 K. However, the magnetoresistance for temperatures below 150K decreases as the temperature decreases. Note that the surprisingly large amount of scatter in the data may be attributable to inadequate time allowed between measurements for thermal equilibrium to be achieved. However, the behavior of the magnetoresistance is very symmetric (hump in the middle) from 150 K and it can be attributed to higher mobility around 150 K [13, 62].

The major difference between the devices C10R13 and C10R17 in Figure 45 was the W/L ratio. The device with higher field sensitivity was the device with a W/L ratio of 0.066 and the device with lowest field sensitivity was the device with a W/L ratio of 0.05. However, as seen in the work of Hoener *et al.* [41], the field sensitivity increases with a decreasing aspect ratio until it reaches a maximum at W/L of 0.05. In this experiment, the highest signal was obtained for the largest W/L ratio. A possible reason for a lower magnetoresistance at the lowest aspect ratio is that the device was too large. Then electrons have enough room to accumulate (caused by the Lorentz force). This charge accumulation decreases the finite field resistance therefore, the EMR effect, which is the Hall effect with geometrical constraints, is not strong enough because the device geometry does not have the optimum dimensions.

5.2.2 Statistical analysis

Every datum in Figure 45 was obtained by calculating the slope of the transfer curve obtained from a magnetic field sweep at a specific temperature. The lines of the transfer curves were obtained with $R^2 = 1$ which means that the fitted line accounted for 100% of the variability in the data. The residual scatter in the field sensitivity as a function of temperature shown in Figure 45 may be due to the sample not being in thermal equilibrium with the sample stage at each measurement point. The user waited no more than 1 minute for the sample to reach thermal equilibrium after the sample's temperature-controller read the target temperature.

An ANOVA analysis of the two groups of data is shown in Table 8 where SS is the sum of squares, df is the degrees of freedom, MS is the mean square, F is the test statistic, F_{crit} is the test statistic for $\alpha = 0.05$, where α is the level of significance, and the P-value is the probability that the statistic analysis on the value had enough weight. Since $F_{crit} > F$ and $P\text{-value} < \alpha$ then this ANOVA analysis has statistical significance on the magnetoresistance [60]. The two EMR devices only differ in their W/L ratio and their EMR values changed depending in this ratio. The effect of the thermal instability is seen in the MS value of twice that of the error.

Table 8. ANOVA analysis.

Source of Variation	SS	df	MS	F	P-value	F crit
Temperature	44.8326	23	1.949244	2.712832	0.010138	2.014424
W/L	1102.045	1	1102.045	1533.755	1.47E-22	4.279343
Error	16.52613	23	0.718527			
Total	1163.404	47				

5.3 Localized field sensitivity

5.3.1 Review of procedures

In this experiment a localized field sensitivity signal was measured following Holz *et al.* [6], Maat *et al.* [46] and, Boone *et al.* [54] model. From their modeling the VIV triad was expected to have most of the magnetoresistive activity and indeed using MSM the highest signal was observed in the VIV triad with a voltage signal of 100 μV when a 60 μA current was applied. Four devices were measured with two different types of tips, a high moment MFM tip and a regular MFM tip. The best resolution images were obtained with regular MFM tips which have a lower magnetic moment and smaller radius of curvature. MFM probes applied fields as large as 800 Oe from the high moment tips and as low as 200 Oe from the small moment tips.

At a first look the MSM signal had a similar shape and intensity as the signal modeled by Maat *et al.* [46] in devices with geometry similar to that of LF4. This can be observed in Figure 46 where the signal obtained in a measured device is compared to the expected signal calculated by Maat *et al.* [46] with FEM modeling. An estimation of the magnetic sensitivity, assuming the signal is purely a magnetic effect, is $(80 \mu\text{V} / 60 \mu\text{A}) / 0.8 \text{ kOe} = 1.6 \Omega/\text{kOe}$.

a) b)
Figure 46. Comparison of a) MSM signal from device LF4 (printed with permission of HGST) and b) FEM modeling by Maat *et al.* [IEEE Intermag, May 2006]. The z-axis shows the voltage signal intensity.

However, from FEM modeling, the largest peak was expected to be the center peak just beside the current lead, and the two side peaks were expected to be smaller and just beside the voltage leads. Figure 46a shows three peaks, where the right most peak is longer with a larger signal than the left most peak. The center peak looks to be like a third peak but 2D images showed that it was part of the right peak (or double peak). The MSM signal obtained was investigated to see if it was purely caused by the magnetic field of the magnetic tip, or was additionally affected by a capacitive effect between the tip and device, or by the force applied by the intermittent contact of the tip while scanning. To study the capacitive effect, MSM was performed with a non-magnetic tip with different voltages applied by the tip and with different field directions. To study the effect of the tip touching the sample, MSM was performed with different lift heights. The results of these experiments are shown in the next sections after some explanation of

the conventions used in the images showed and the effect of the current direction in the MSM signal.

5.3.2 Geometry and conventions

MSM images of the four devices, LF1, LF2, LF3 and LF4, had two discernible peaks just beside each voltage lead and both corresponding to the probe being above the 2DEG mesa. None of the devices showed a peak beside the current lead as expected based on FEM modeling [46]. The shape of the regions, which showed magnetoresistance sensitivity, changed somewhat depending on the lead-to-lead distance. Devices LF1 and LF3 had the largest lead to lead distance and the peaks were the most easily resolved, showing more detail in the voltage signal. A signal typical of devices LF1 and LF3 is shown in Figure 47 with peaks that had two or three easily resolved concentric bands. A signal typical of devices LF2 and LF4 is shown in Figure 58.

By convention the peak that was beside the positive voltage lead was called V^+ and the peak that was beside the negative voltage lead was called V^- as shown in Figures 47 and 48. Note that the peak V^+ was uppermost in the images of devices LF1 and LF3, but lowest in images of LF2 and LF4, since the sample was rotated between these measurements.

Figure 47. Location and convention of MSM signal (LF1). a) V+/V- convention, b) overlay of MSM signal and AFM topography showing location of peaks and, c) mask design of the device (printed with permission of HGST).

Figure 48. Location and convention of MSM signal (LF2). a) V+/V- convention, b) overlay of MSM signal and AFM topography showing location of peaks and, c) mask design of the device (printed with permission of HGST).

5.3.3 Current polarity

Current polarity was observed to influence the intensity of the MSM signal. The signal obtained for a positive current (with electrons being injected at the current lead I+ of Figure 26) was generally larger, and in some cases as much as twice that for negative current (where electrons are injected into the device at current lead). This is illustrated in Table 9 and Figures 49 and 50.

Table 9. Measurements with different current polarities.

LF1	V+(top peak) [μV]	V- (bottom lead)[μV]
60 μA	104	108
-60 μA	49	64

Figure 49. a) MSM with +60 μA and b) overlay of the signal on the AFM image. Scanned with MESP tip and lift height of 0 nm (printed with permission of HGST).

Figure 50. MSM with $-60 \mu\text{A}$ and overlay of the signal on the AFM image. Scanned with MESP tip and lift height of 0nm (printed with permission of HGST).

Note that the upper voltage signal (V^+) showed a value of $104.3 \mu\text{V}$ for $+60 \mu\text{A}$ and $49.7 \mu\text{V}$ for $-60 \mu\text{A}$. This was expected since injecting electrons in the device at the I^+ lead or I^- lead results in opposite Lorentz forces acting on the carriers in the sensitive region, for a given applied magnetic field (from the tip in this case) and a given bias current. The asymmetry in signal with applied current direction is not expected from purely diffusive scattering of carriers, possibly suggesting some ballistic like behavior near the triad when electrons are injected into the I^- lead.

5.3.4 Lift height measurements

To reveal if the MSM signal obtained was influenced by intermittent contact between the tip and sample while scanning, a scan with different tip-sample separations was performed by varying the SPM's lift-height parameter. Table 10 and Figure 51 shows the MSM signal for different heights. Increasing the tip-sample separation to 10 nm had no statistical significance on the signal strength. Therefore, it is concluded that the tapping of the tip on the sample is not the origin of any of the signal obtained in these measurements.

Table 10. Lift height measurements.

Lift Height [nm] on R3C1		0	5	10
60 μ A	V+ [μ V]	56.2	59.2	62.0
	V- [μ V]	38.5	42.5	38.0
-60 μ A	V+ [μ V]	27.7	25.3	27.1
	V- [μ V]	30.6	44.6	46.0

Figure 51. Lift height measurements (printed with permission of HGST).

5.3.5 MSM with a non-magnetic metallic probe

A hypothesis was that the MSM signal obtained might have included a capacitive effect arising from an electrical potential difference between the tip and sample, as might arise there were stray electric charges on the tip. It is very difficult to remove all the charges from such a high aspect ratio nanoscale feature. Bringing a charged object close to the 2DEG could have the same effect as biasing the gate in a FET (Field-effect Transistor). To explore this possibility MSM was performed with a non-magnetic metallic tip, and this experiment showed a similar MSM signal to that collected with the magnetic tips. Tables 11 and 12 show measurements with two types of tips, one with a coating of 300 Å PtIr used for Electric Force Microscopy (EFM) manufactured by Veeco and one with a coating of TiPt manufactured by μ Mash. This experiment indicated that

much, if not all, of the signal that had been seen when scanning with magnetic tips was likely due to stray charges on the tip interacting capacitively with the 2DEG in the EMR devices. An overlay of the MSM signal with the AFM signal is shown in Figure 52. After proving the influence of a capacitive effect, every tip used was de-ionized with a de-ionizing nitrogen jet that blows charge off the sample and a polonium 210 source was placed in close proximity to the sample during imaging to minimize charging on each surface.

To explore this effect further, a small bias voltage was applied to the tip to attempt to control the capacitive signal size. It was anticipated that if good control over the tip charging (positive and negative) could be achieved then it might be possible to subtract entirely the capacitive portion of the signal obtained with magnetically coated tips, leaving a 'pure' magnetic signal.

Accordingly, MSM was performed with a non-magnetic tip with an applied voltage. These measurements are shown in Table 12. Figure 53 shows that the response to the applied voltage on the tip was not linear with tip voltage over the range measured, which could be understood as a result of the pyramidal tip geometry.

Table 11. 300Å Pt tip measurements.

Pt probe (grounded tip)	μV
V-	15.2
V+	17.7

Figure 52. Overlay of AFM with MSM signal collected with a non-magnetic metallic tip (applied current +60 μA). Obtained using the subtraction software of the DI3100 (printed with permission of HGST).

Table 12. Measurements with TiPt μMash tip

Tip Bias (R4C2) [μV]		-3V	-1V	Ground	1V
60 μA	V^+	301	274	108	168
	V^-	627	320	126	219

As more electrons (or holes) were added to the apex of the tip, charge density limitations will force them to be localized higher and higher up the tip coating (further away from the sample), hence each added unit of charge would be expected to increase the MSM signal through capacitive interactions by a smaller amount than the previous

unit of charge added to the tip. However more measurements at smaller voltages should be done to see the nature of the interaction with small amounts of charge on the tip.

Figure 53. MSM signal with tip bias (TiPt from μ Mash) (printed with permission of HGST).

5.3.6 Change of field direction

Another approach that was taken to clarify the relative influence on the MSM signal of the charge on the tip and the magnetic field of the tip was to image with tips that were magnetized in opposite fields (hereafter labeled arbitrarily B_{up} and B_{down}). The hypothesis was that when the direction of the magnetic tip was changed, the Lorentz forces acting on the carriers in the EMR device would reverse, causing changes in the shape, magnitude and location of the MSM signal peak, although these differences may be quite small if electrostatic effects dominate.

This experiment was performed with opposite currents and repeated to check reproducibility. Signals obtained in the first try were generally larger than signals

obtained in the second try, which was likely a result of some damage to the metallic film of the tip during imaging – and is not uncommon, as shown in Figure 54. When the applied current was positive the MSM signal was larger with B_{down} and when the applied current was negative the MSM signal was larger with B_{up} , as shown in Table 13. Figures 56 and 57 show the MSM images with B_{up} and B_{down} respectively and $I = 0\text{V}$. The peak shape and peak signal strength changes. Figure 55 shows the percent change in the MSM signal when changing the field direction and that this change was largely reproducible (with some variance) for the two peaks (V+ and V-) and current direction.

Figure 58 shows a MSM image that was the result of the subtraction of two MSM images obtained with opposite magnetic fields. This subtraction was intended to remove the electrostatic effects and reflect the magnetic signal. Because signals with similar conditions that only differ in the magnetic field direction were subtracted, the capacitive component of the signal should be eliminated (assuming that the electrical state of the tip had not changed and assuming the magnetic and electrical effects superpose linearly) making this difference only magnetic in origin. The image is made even more confusing by the subtracting function provided by Veeco (SPM and tip manufacturer) which yields only the absolute value of the difference, leading to some ambiguity in the image. Therefore the MSM signal obtained, although likely to have some magnetic component, cannot be conclusively identified with the localized magnetic excitation alone. More work is required to resolve the complexities of the measurement, including reducing the electric potential between tip and sample, modeling to determine how easy electrostatic

effects can be separated from magnetic effects, and improvement in the image subtraction software.

Table 13. Effect of field direction on MSM signal

Applied Current	Voltage Contacts	B _{down}		B _{up}	
60 μ A	V- [μ V]	95	55	75	47
	V+ [μ V]	140	93	97	76
-60 μ A	V- [μ V]	83	64	81	60
	V+ [μ V]	90	69	106	132

Figure 54. MSM signal for opposite tip magnetizations. Signal measured in the V+ peak and V- peak (printed with permission of HGST).

Figure 55. Percentage changes from B_{up} to B_{down} in two consecutive experiments (printed with permission of HGST).

Figure 56. B_{down} : a) MSM signal and b) overlay with topography (printed with permission of HGST).

CHAPTER SIX CONCLUSIONS

The objective of this project was the characterization of EMR devices, in terms of resistance, carrier concentration, sheet resistance, device geometry, and IV configuration in homogeneous and localized magnetic fields.

The sheet resistance, Hall mobility and carrier concentration obtained from measurements of vdP devices were in agreement to those obtained by Boone *et al.* [13] and assumed by Maat *et al.* [46]. Measurements showed that as expected decreasing the distance of the 2DEG from the surface increased the carrier concentration. The Hall mobility was expected to decrease as the 2DEG was brought closer to the surface; however, it did not change. Also, measurements confirmed that processing did not alter the transport properties of the 2DEG, and that the method and instrumentation used for transport properties characterization lead to reproducible results since transport properties values obtained at HGST matched those obtained by the wafer vendor.

Under a homogeneous field, devices with two different aspect ratios were characterized. They showed similar MR vs. temperature behavior with an MR that was almost constant with temperature. The device that had the highest MR value was the device with the highest aspect ratio in contradiction with earlier modeling results [41]. The reason for this was that the devices were too large giving enough room for charge accumulation. This experiment provided guidance for future characterization in the range from 60 K to 240 K (centered at 150 K) because was in that range that there was a shallow peak which may be associated with an added conduction channel becoming

accessible to carriers at these temperatures. Thermal drift may have caused some of the data spreading and should be avoided in future measurements. The EMR signal achieved in these devices was 5 times ($26 \text{ } \Omega/\text{kOe}$ with $10 \text{ } \mu\text{A}$ versus $5 \text{ } \Omega/\text{kOe}$ with $100 \text{ } \mu\text{A}$, see section 5.2.1) the EMR reached by the devices characterized by Boone *et al.* [54].

The localized field experiments were performed on four devices, and a signal of around $100 \text{ } \mu\text{V}$ (with a current of $60 \text{ } \mu\text{A}$) was obtained when a magnetic probe of 800 Oe was used. This signal was different for different device geometries and, in contrast with the homogeneous field measurements, the signal was larger for the lowest W/L ratio. Devices of wafers HF and LF had similar dimensions ($L = 9 \text{ } \mu\text{m}$ and widths 450 nm and 600 nm). Therefore, they could be compared in terms of W/L ratio. The peaks that were the most easily resolved, were in the devices with the largest spacing between the tabs which was expected since the magnetic probe limited the spatial resolution. The MSM signal was always larger for positive currents, and the signal shape depended on the geometry.

The MSM signal observed was influenced greatly by capacitive interactions between the tip and the sample. The capacitive effect was non-linear with tip-bias out to 3V , but further experiments at low bias may allow control over tip charging to a sufficient degree that the capacitive influence could be removed from the otherwise magnetic part of the MSM signal. After subtracting two traces taken with an oppositely magnetized tip a signal remained which may be the magnetic component in the MSM signal. This difference signal was reproducible, showing that more detailed experiments,

combined with modeling of the combined effects of electrostatic and magnetostatic excitation should yield an understanding of the magnetic component of the MSM signal.

Further, future plans include reducing the capacitive signal to a sufficiently low amplitude that there is a high degree of confidence to be able to subtract subsequent images. For that we need either more MSM measurements with different tip bias or to remove the capacitive signal component by subtracting images taken with opposite magnetic fields on the tip, or to reliably zero the potential between the tip and device.

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APPENDIX A

Table 14. Sheet resistance calculations.

Sheet Resistance Calculations					
Current	(mA)	Voltage	(V)	Resistance	(Ω)
I_{21}	1	V_{34}	0.104	$R_{21,34}$	104.0
I_{12}	1	V_{43}	0.104	$R_{12,43}$	104.0
I_{32}	1	V_{41}	0.081	$R_{32,41}$	80.8
I_{23}	1	V_{14}	0.081	$R_{23,14}$	80.9
I_{43}	1	V_{12}	0.104	$R_{43,12}$	104.0
I_{34}	1	V_{21}	0.104	$R_{34,21}$	104.0
I_{14}	1	V_{23}	0.081	$R_{14,23}$	81.0
I_{41}	1	V_{32}	0.081	$R_{41,32}$	80.5
Sheet Resistance Calculations					
$R_A = (R_{21,34} + R_{12,43} + R_{43,12} + R_{34,21})/4$ (ohms)					104.0
$R_B = (R_{32,41} + R_{23,14} + R_{14,23} + R_{41,32})/4$ (ohms)					80.8
$z_0 = 2 \ln(2) / [\pi (R_A + R_B)]$					0.0023878
$y_1 = 1 / \exp(\pi z_0 R_A) + 1 / \exp(\pi z_0 R_B)$					1.003788
$z_1 = z_0 - [(1-y_1)/\pi] / [R_A / \exp(\pi z_0 R_A) + R_B / \exp(\pi z_0 R_B)]$					0.0024010
$y_2 = 1 / \exp(\pi z_1 R_A) + 1 / \exp(\pi z_1 R_B)$					1.0000073
$z_2 = z_1 - [(1-y_2)/\pi] / [R_A / \exp(\pi z_1 R_A) + R_B / \exp(\pi z_1 R_B)]$					0.0024010
Check: $(z_2 - z_1) / z_2 < 0.0005$					good
Sheet resistance, $R_S = 1 / z_2$ (Ω/sq)					416.5
Resistivity, $\rho = R_S d$ ($\Omega\text{-cm}$)					0.0052

Table 15. Hall mobility and carrier concentration calculations.

Hall Voltage Measurements				
Current	mA	Voltage	(V)	Field, B (G)
I_{13}	1	V_{24P}	-0.263	5000
I_{31}	1	V_{42P}	-0.264	5000
I_{42}	1	V_{13P}	-0.216	5000
I_{24}	1	V_{31P}	-0.216	5000
I_{13}	1	V_{24N}	0.215	-5000
I_{31}	1	V_{42N}	0.215	-5000
I_{42}	1	V_{13N}	0.262	-5000
I_{24}	1	V_{31N}	0.262	-5000
Hall Calculations				
$V_C = V_{24P} - V_{24N}$				-0.4780
$V_D = V_{42P} - V_{42N}$				-0.4790
$V_E = V_{13P} - V_{13N}$				-0.4780
$V_F = V_{31P} - V_{31N}$				-0.4780
$V_C + V_D + V_E + V_F$				-1.9130
Sample type				n-type
Sheet carrier density, n_s or p_s				
$= \text{abs}(8E-8 I B / [q(V_C + V_D + V_E + V_F)]) \text{ (cm}^{-2}\text{)}$				1.31E+12
Bulk carrier density, $n = n_s/d$ or $p = p_s/d \text{ (cm}^{-3}\text{)}$				1.04E+18
Hall mobility, $\mu = 1/qn_s R_s \text{ (cm}^2\text{V}^{-1}\text{s}^{-1}\text{)}$				1.15E+04

APPENDIX B

Table 16. Transfer curves used to obtain EMR temperature dependence illustrated in Figure 39. Temperatures 300 K- 130 K.

Transfer Curves for R17 C15		
Temperature [K]	Transfer Curve	Magnetic sensitivity [Ω/kOe]
300	$y = 12.606x + 78.182$	12.606
290	$y = 12.785x + 80.856$	12.785
280	$y = 13.751x + 82.219$	13.751
270	$y = 13.135x + 71.225$	13.135
260	$y = 13.691x + 63.472$	13.691
250	$y = 14.735x + 61.116$	14.735
230	$y = 14.825x + 67.882$	14.825
240	$y = 14.735x + 66.913$	14.735
220	$y = 13.882x + 70.256$	13.882
210	$y = 14.722x + 69.831$	14.722
200	$y = 16.062x + 75.639$	16.062
190	$y = 15.364x + 68.581$	15.364
180	$y = 15.524x + 72.731$	15.524
170	$y = 15.571x + 77.866$	15.571
160	$y = 14.969x + 81.764$	14.969
150	$y = 15.505x + 88.119$	15.505
140	$y = 15.059x + 95.154$	15.059
130	$y = 16.006x + 115.72$	16.006

Table 17. Transfer Curves used to obtain EMR temperature dependence illustrated in Figure 39. Temperatures 120 K- 5 K.

Transfer curves for R17 C15		
120	$y = 16.003x + 125.19$	16.003
110	$y = 16.075x + 121.26$	16.075
100	$y = 14.865x + 110.96$	14.865
90	$y = 15.606x + 112.88$	15.606
80	$y = 16.81x + 115.68$	16.81
75	$y = 15.065x + 111.77$	15.065
70	$y = 14.394x + 108.3$	14.394
65	$y = 15.024x + 114.07$	15.024
60	$y = 14.305x + 112$	14.305
55	$y = 14.39x + 117.9$	14.39
50	$y = 15.184x + 165.71$	15.184
45	$y = 15.061x + 170.05$	15.061
40	$y = 14.83x + 170.71$	14.83
35	$y = 14.583x + 176.44$	14.583
30	$y = 15.284x + 167.46$	15.284
25	$y = 13.696x + 165.96$	13.696
20	$Y = 13.987x + 172.75$	13.987
15	$y = 14.058x + 163.78$	14.058
10	$y = 13.875x + 170.03$	13.875
5	$y = 13.958x + 162.37$	13.958

Table 18. Transfer Curves used to obtain EMR temperature dependence illustrated in Figure 39. Temperatures 5 K- 240 K.

Transfer Curves for R13C10		
Temperature [K]	Transfer curve	Ω/kOe
5	$y = 21.42x - 27.345$	21.42
20	$y = 22.46x - 27.53$	22.46
30	$y = 21.83x - 16.767$	21.83
40	$y = 25.78x - 24.213$	25.78
50	$y = 23.74 - 14.567$	23.74
60	$y = 23.97x - 21.405$	23.97
70	$y = 24.15 x - 13.714$	24.15
80	$y = 24.43 x - 20.62$	24.43
90	$y = 25.18 x - 19.817$	25.18
100	$y = 25.04 x - 13.739$	25.04
110	$y = 25.84 x - 24.523$	25.84
120	$y = 26.44 x - 13.59$	26.44
130	$y = 26.81 x - 20.77$	26.81
140	$y = 26.72 x - 13.468$	26.72
150	$y = 24.91 x - 11.794$	24.91
160	$y = 26.24 x - 20.12$	26.24
170	$y = 25.59 x - 12.794$	25.59
180	$y = 25.19 x - 19.243$	25.19
190	$y = 257.88x - 17.097$	25.7
200	$y = 253.48x - 11.847$	25.3