Imaging Capability of PHEMT, GaN/AlGaN and Si Micro Hall Probes for Scanning Hall Probe Microscopy between 25-125 ^{o}C

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We present a comparative study on imaging capabilities of three different micro hall probe sensors fabricated from narrow and wide band gap semiconductors for scanning hall probe microscopy (SHPM) at variable temperatures. A novel method of Quartz tuning fork AFM feedback has been used which provides extremely simple operation in atmospheric pressures, high-vacuum and variable-temperature environments and enables very high magnetic and reasonable topographic resolution to be achieved simultaneously. Micro Hall probes were produced using optical lithography and reactive ion etching process. The active area of all different types of Hall probes were 1µm x 1µm. Electrical and magnetic characteristics shows Hall coefficient, carrier concentration and series resistance of the hall sensors to be 10mΩ/G, 6.3 x 10^{12}cm^{-2} and 12kΩ at 25^{o}C and 7mΩ/G, 8.9 x 10^{12}cm^{-2} and 24kΩ at 125^{o}C for GaN/AlGaN two–dimensional electron gas (2DEG), 0.281mΩ/G, 2.2 x 10^{14}cm-2 and 139kΩ at 25 ^{o}C and 0.418mΩ/G, 1.5 x 10^{14}cm^{-2} and 155kΩ at 100^{o}C for Si and 5-10mΩ/G, 6.25 x 10^{12}cm^{-2} and 12kΩ at 25^{o}C for PHEMT 2DEG Hall probe. Scan of magnetic field and topography of hard disc sample at variable temperatures using all three kinds of probes are presented. The best low noise image was achieved at temperature of 25^{o}C, 100^{o}C and 125^{o}C for PHEMT, Si and GaN/AlGaN Hall probes respectively. This upper limit on the working temperature can be associated with their band gaps and noise associated with thermal activation of carriers at high temperatures.

***Index Terms*— Atomic force microscopy, GaN/AlGaN heterostructure, Hall Probe, Quartz Tuning Fork, Scanning Hall Probe Microscopy.**

I. INTRODUCTION

THE growing interest in the investigation of localized surface magnetic field fluctuation at variable temperatures with high spatial resolution and for non metallic samples has made the scanning Hall probe microscopy (SHPM) with quartz tuning fork AFM feedback technique to be the one of the best choice as it provide means to perform sensitive, noninvasive, and quantitative imaging capabilities. SHPM technique offers various advantages and complements the other magnetic imaging methods like Scanning Superconducting Quantum Interference Device Microscopy (SSM) [2], Magnetic Force Microscopy (MFM) [3], Magnetic Near Field Scanning Optical Microscopy [4] and Kerr Microscopy [5]. However, there have been few reports [6, 7] on magnetic imaging with Hall sensors at high temperature regime.

In this study we have investigated different kinds of heterostructures, AlGaN/GaN heterostructure, SOI, and PHEMT heterostructure, for their electrical and magnetic properties at variable temperatures (25^{o}C to 125^{o}C). In general two dimensional electron gas (2DEG) materials with high band gap (greater than 2.5eV), like AlGaN/GaN, offer the advantage of being physical hard and it helps in reducing the possibility of thermally induced intrinsic conduction and existence of a high mobility of a two dimensional electron gas layer which greatly enhances the magnetic sensitivity of Hall sensors. On the other hand 2DEG material with low band gap, like PHEMT, offers high response level and thus helps in increasing the sensitivity of the system. On the other hand due to cmos compatibility SOI structures have been also investigated for their application in hall effect sensors.

The imaging capability of 1um x 1um hall probes from all three types materials have been explored by scanning a hard disc sample using scanning Hall probe microscopy with Quartz tuning fork for a temperature range of 25-125^{o}C.

II. FABRICATION AND CHARACTERIZATION

A. Fabrication

1) Wafer Specifications

The AlGaN/GaN 2DEG semiconductor wafers used in this study were grown on Si (111) by rotating disc MOCVD material [8]. The epistructure of the wafer, as shown in Fig. 1a (a), consist of the following layers; 1) a 20Å thin layer of GaN cap layer for protection purposes, 2) 180Å of Al0.26Ga0.74N layer, 3) 1µm thick layer of undoped GaN, which forms a 2 DEG at the AlGaN interface, 4) proprietary stress mitigating transition layer of 1.1µm, and 5) High resistivity Si (111) substrate with a resistivity of 10kΩcm. The room temperature sheet carrier concentration and electron mobility of the 2DEG induced at the hetero-interface were 2 x 10^{12} cm^{-2} and 1,500 cm^{2}/Vs, respectively.

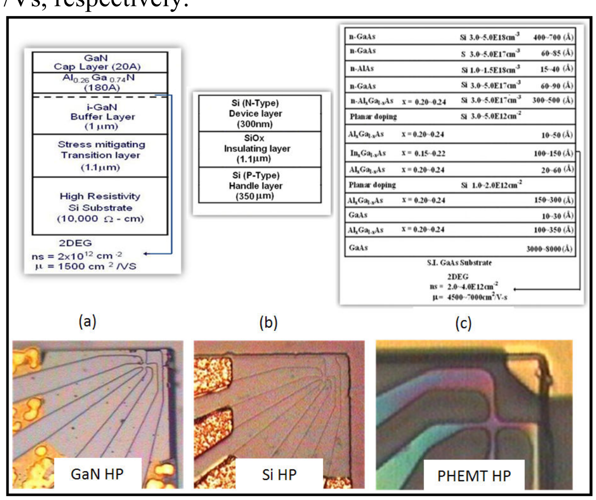

Fig. 1. Schematic diagram of the layer configuration of the AlGaN/GaN heterostructure (a), SOI wafer (b) and PHEMT heterostruture (c) and corresponding photographs of 1µm x 1µm Hall probes.

SOI wafer with thermal oxide thickness of this has been used after thinning the device layer down to few hundred nm. The epistructure of the wafer, as shown in Fig. 1b, n-type device layer, 2) Thermal Oxide SiOx and 3) p-type handle layer. The room temperature sheet carrier concentration was 2.2 x 10^{14} cm^{-2}.

PHEMT two dimensional electron gas (2DEG) semiconductor wafers used in this study were grown by MBE on GaAs Substrate. The epistructure of the wafer, as shown in Fig. 1c, consist of the following layers; 1) cap layers for protection purposes with high doping concentration, 2) 2DEG structure, 3) Semi Insulating GaAs Substrate. The room temperature sheet carrier concentration and electron mobility of the 2DEG induced at the hetero-interface were 2 - 4 x 10^{12} cm^{-2} and 4,500~7000 cm^2/Vs, respectively.

1) Device Fabrication

Micro Hall probes with effective dimension of 1μm x 1μm have been fabricated using optical lithography in a class 100 clean room environment. Device fabrication process consists of three major steps which are: 1) formation of the mesa and active “cross” patterns by reactive ion etching (RIE); (2) thermal evaporation of Ohmic contacts; and (3) rapid thermal processing (RTP) in a nitrogen atmosphere.

Fabrication parameters are summarized in Table 1. Four Hall sensors are micro fabricated on a 5mm × 5mm chip at a time and they are diced to a size of 1mm × 1mm × 0.5mm. The photographs of the fabricated Hall probe are shown in Fig. 1. In order to investigate the electrical characteristics of Hall probes electrical connection have been established with 12μm gold wire using ultrasonic wedge bonder.

TABLE I

DEVICE FABRICATION PROCESS AND PARAMETERS

Process	GaN/AlGaN	Si	PHEMT
Cap Layer ETCH	--	--	Wet Etch with H2SO4
MESA + Recess	RIE with CCL_2F_2	RIE for Si with SF6+O2 RIE for Si with SF6+O2	RIE with CCL_2F_2
Hall Cross Definition	RIE with CCL_2F_2	RIE with CCL_2F_2	RIE with CCL_2F_2
Ohmic Contact	Ti/Al/Ti/Au	Ti/Au	Cr/Au
RTP	850°C for 30sec	400°C for 30sec	--
Bonding Metallization	Ti/Au	--	--
Bonding	12μm gold wire	12μm gold wire	12μm gold wire

B. Electrical and Magnetic Characterization

1) Electrical Characteristics

Hall Sensors have been characterized based on their electrical characteristics (Hall voltage (V_H) vs. Hall current (I_H)) up to bias temperatures from 25°C to 125°C. As shown in Fig. 2, a linear relations can be observed between V_H vs. I_H characteristics with two different dynamic resistances (slope of V_H vs. I_H curve, $r_H = V_H / I_H$) regimes. These regimes are low current regime ($I_H \leq 100\mu A$) and high current regime ($I_H > 100\mu A$).

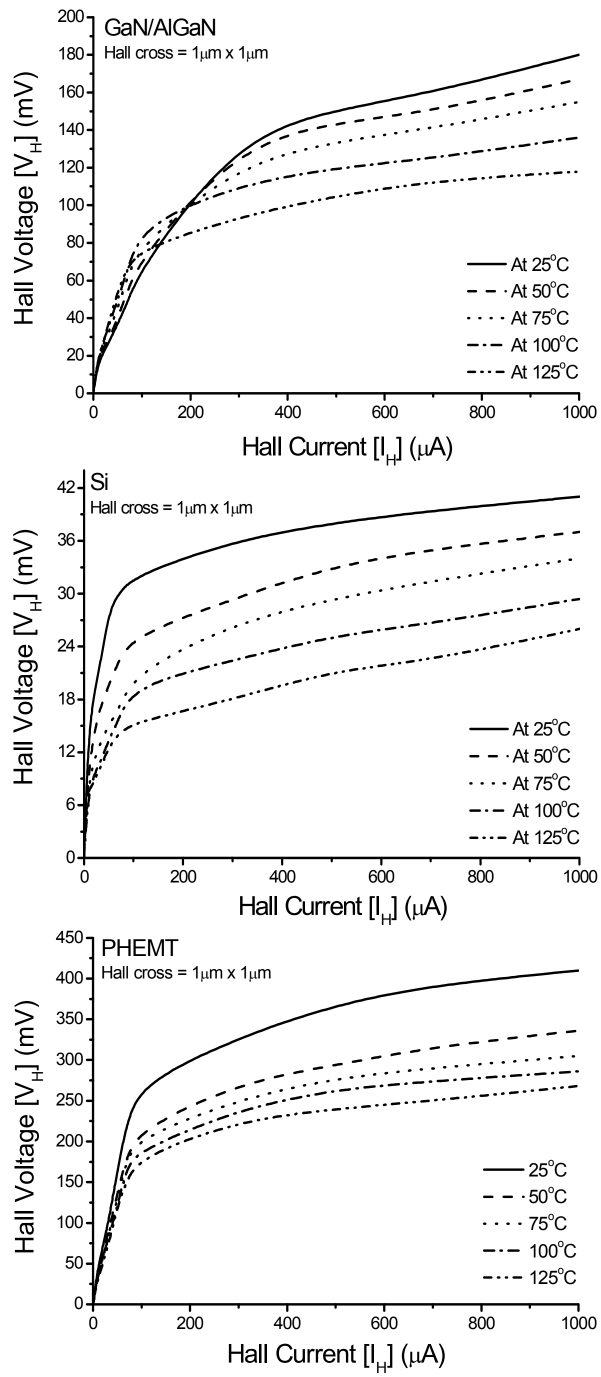

FIG. 2. Effect of Temperature on the Hall Voltage vs. Hall current characteristics for all three types of micro Hall probes.

Under the high bias current conditions effect of temperature on the V_H vs. I_H characteristics can be quantified as a decrease in the V_H for a particular current value. This percentage decrease is 31%, 44 % and 35% for GaN, Si and PHEMT Hall probes respectively for a bias current of 500μA. On the other hand in the low current regime GaN hall probe show an increase by 47% in the V_H vs. I_H characteristics compared to a decrease of 55% and 27% for Si and PHEMT Hall probes respectively. This comparison shows that for high temperature applications GaN probes are better than Si and PHEMT. While on the other by increasing current from 50μA to 500μA for a fixed temperature this increase is 310% for 25°C and 95% at 125°C for GaN, but for Si this increase is just 25% and 68% and PHEMT shows 124% and 123%. This percentage comparison also confirms that GaN Hall probes are better for high temperature applications with low bias current which in other words confirms the low noise operation as well.

In general for all three probes r_H value gets decreased by increasing the current from low current regime to high current regime at any particular bias temperature condition. It is speculated that this decrease in the r_H value is due to that there might be opening of new conduction channels by applying high current causing an increase in the number of parallel paths. This argument can be supported by using the above mentioned temperature dependent comparison.

2) *Magnetic Characterization*

Hall probes have been also characterized for their magnetic response by applying magnetic field with an external coil and by measuring the Hall voltage to calculate the value of Hall coefficient, R_H. As shown in Fig. 3, value of R_H also depends on the Hall current and two regimes can be formed as in the case of V_H vs. I_H.

Similar comparison as presented in the previous section is summarized for magnetic characteristics in the table II. Based on these results we can say that PHEMT probes are the worse choice to be used for high temperature SHPM applications while though Si show more percentage increase in the case of increase in current and increase in temperature compared to GaN but the values of R_H are very less compared to that of GaN Hall probes. Another observation based on the temperature dependence In general R_H value is more current depend for high current regime for GaN HPs but it is opposite for Si and PHEMT cases.

TABLE II
MAGNETIC CHARACTERISTICS OF HALL PROBES

HP type / Bias Current (For a change of Temp from 25°C to 12°C)	**50μA**	**100μA**
AlGaN / GaN	10% ↑	40% ↓
Si	110% ↑	75% ↑
PHEMT	7% ↓	14% ↓

HP type / Temperature *(For a change of I_H from 50μA to 500μA)*	**25°C**	**125°C**
AlGaN / GaN	190% ↑	433% ↑
Si	262% ↑	337% ↑
PHEMT	78% ↓	80% ↓

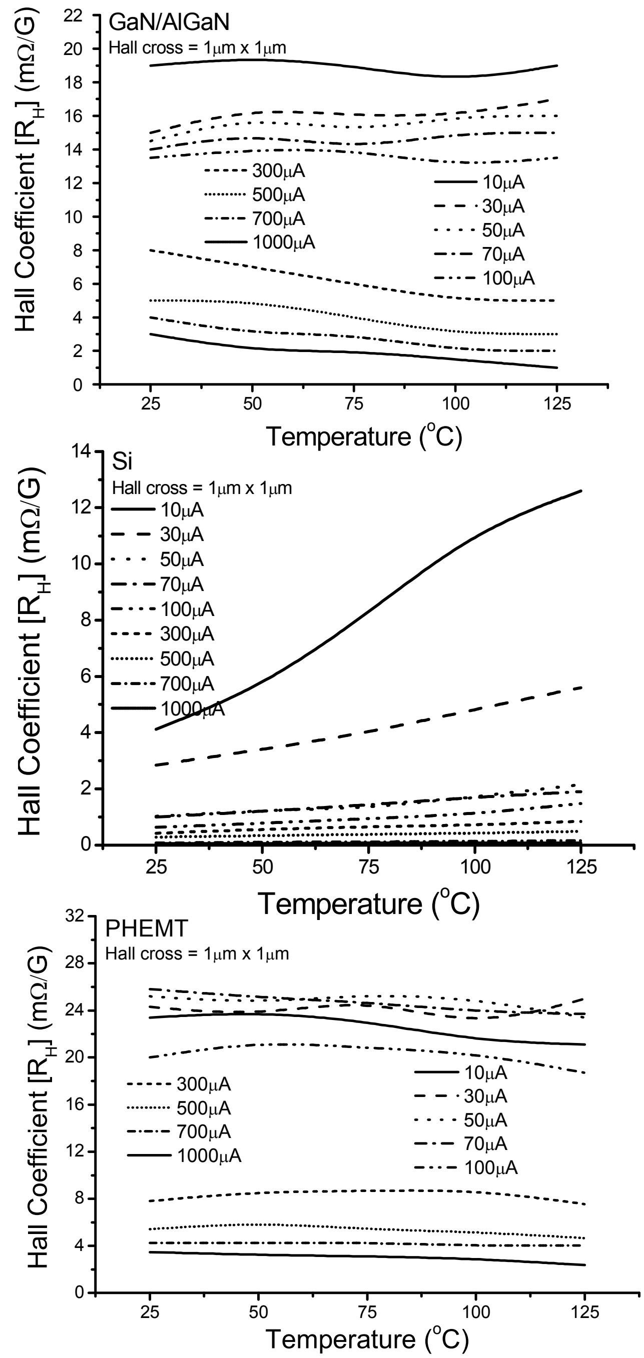

Fig. 3. Effect of Hall current on Hall coefficient vs. Temperature characterization of all three types of Hall probes.

During the experiments, the scanning sensor remains at high temperatures for long period of times. We have investigated run time effect on V_H vs. I_H and R_H vs. I_H characteristics under high temperature environments. The results showed no significant change in the values for the case of GaN while a decrease detrition of signal level has been observed for the other two types of probes, suggesting a safe use of GaN Hall probes in scanning systems over a long time in harsh conditions.

III. Scanning Hall Probe Microscopy

A. *Scanning Results and discussion*

A commercial Low Temperature-SHPM system [9] with some modifications for high temperature measurements is used to perform the scanning experiments. This scanning Hall probe microscope can operate under two different feedback schemes namely, STM and AFM. As mentioned in the introduction, in order to compensate the drawbacks of STM feedback especially at high temperatures a novel method of quartz tuning fork AFM feedback has been implemented. A 32.768 kHz Quartz crystals tuning forks with stiffness of 29 kN/m has been used for AFM feedback. In order to integrate these force sensors in SHPM, they are extracted from their cans and their leads have been replaced with a non magnetic wiring. Furthermore these Quartz tuning forks are glued to a 10mm × 10mm printed circuit board sensor holder compatible with the scanning head of SHPM system. Hall probe with chip size of 1mm x 1mm x 0.5mm has been mounted on the Quartz tuning fork using super glue. Fig. 4 shows the assembly of Hall probe on a Quartz tuning fork. The detailed analyses of the Quartz tuning fork hall probes microscope technique are presented somewhere else [10].

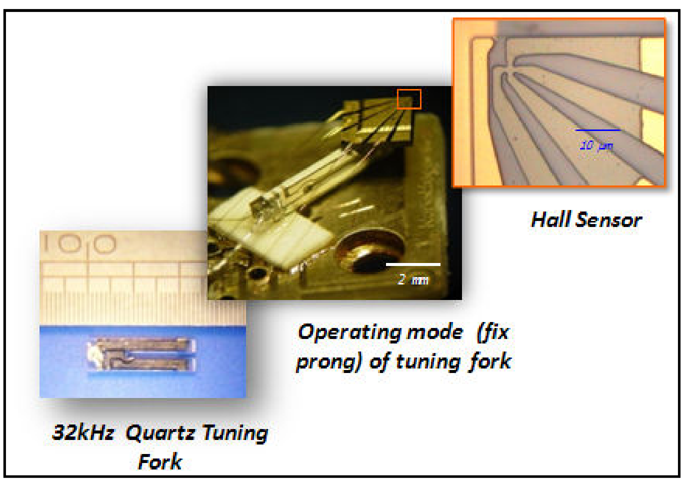

Fig. 4. Integration of micro Hall probe with Quartz Tuning fork with Gold wire for electrical contacts. One prong fixed to the base to reduce the noise and improve the resonance properties of the tuning fork [10].

The Hall sensor is positioned 12µm away from corner of a deep etch mesa, which serves as a crude AFM tip. The sample is tilted ~1°- 2° with respect to Hall probe chip ensuring that the corner of the mesa is the highest point. As the combined sensor is approached to the surface, the resonant frequency of the sensor shifts due to tip sample forces. The sensor assembly is dithered at the resonance frequency with the dedicated split section on the scan piezo tube using a digital Phase Locked Loop (PLL) circuit. The frequency shift Δf, measured by the PLL circuit is used for AFM feedback to keep the sensor sample separation constant with the feedback loop. The microscope can be operated in two modes: AFM tracking and lift-off mode. In our scanning experiments we have used the AFM tracking mode with a Δf (amount of frequency shift) = 10Hz. Furthermore in order to detect AFM topography and the error signal generated by the PLL, along with the magnetic field image, SHPM Electronics is modified. Even though a relatively heavy mass is attached at the end of tuning fork, we usually get a quality factor, Q, 150-220 even at atmospheric pressures. Despite more or less the planar geometry, the viscous damping is not a big problem due to high stiffness of the force sensor.

B. *Scanning Results and discussion*

For an easy comparison on the imaging performance of these three different types of Hall probes we have imaged magnetic bits of the Hard Disk at various temperatures. The Hall sensor was driven with 500µA DC current, the series resistance of the Hall sensors were 9-12kΩ, 80-95KΩ and 26-35kΩ at 25°C for GaN, Si and PHEMT hall probes respectively.

In order to investigate the high temperature operation of these micro Hall probes, a low noise heater stage has been embedded in the LT system. The results of magnetic image of Hard Disk sample obtained in AFM tracking mode at 25°C to 125°C with a scanning speed of 5µm/s and scan area of 50µm x 50µm resolution of 256 x 256 pixel shown in Fig. 4.

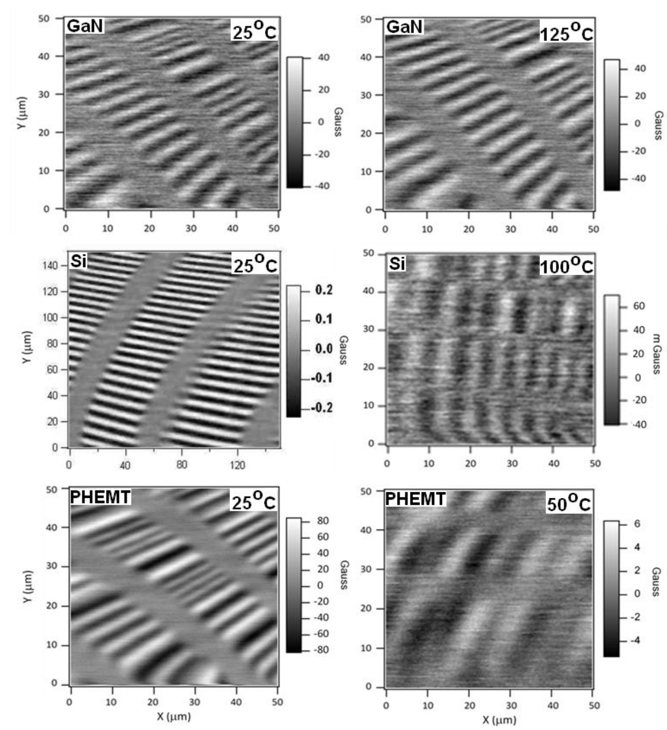

Fig. 4. SHPM image of hard disk sample at high temperatures. Scanning speed was 5µm/s.

The observed distortions in the scanned images at high temperatures are considered to be not due to performance of the Hall probe but it is mainly due to the properties of the QTF and the problems related with the used glue and degradation of the sample.

IV. Conclusion

Comparative study on the application of micro hall probes fabricated by AlGaN/AlGaN, Si and PHEMT at high temperature scanning hall probe microscopy has been presented in this study. These Hall probes have been integrated with quartz tuning fork and successfully used in scanning Hall probe microscopy. Electrical and magnetic characteristics for all three types of probes have shown a division of the characteristics, based on the bias current level at any particular biased temperature. Through study of electrical and magnetic characteristics shows that GaN HP is best choice for an application in high temperature SHPM system compared to other two types. The confirmatory SHPM results of a hard disk sample for temperature range of 25°C to 125°C has been presented to show that out of these three probes GaN micro Hall probes are better for high temperature ranges but comparison of the images makes PHEMTs to be good choice at room temperature. While on the other hand due to complex structure of PHEMT and AlGaN/GaN 2DEG structures, it makes Si to be considerable choice due to its relative good imaging capability and CMOS compatibility to be used for room temperature and batch processing applications. Further study on the investigation of sub-micron devices and selection of other possible high temperature Hall probes are under investigation.

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