Imaging capability of pseudomorphic high electron mobility transistors, AlGaN/GaN, and Si micro-Hall probes for scanning Hall probe microscopy between 25 and 125 °C

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The authors 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 at variable temperatures. A novel method of quartz tuning fork atomic force microscopy 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 1×1 μm^2. Electrical and magnetic characteristics show Hall coefficient, carrier concentration, and series resistance of the hall sensors to be 10 mΩ/G, 6.3×10^{12} cm^{-2}, and 12 kΩ at 25 °C and 7 mΩ/G, 8.9×10^{12} cm^{-2} and 24 kΩ at 125 °C for AlGaN/GaN two-dimensional electron gas (2DEG), 0.281 mΩ/G, 2.2×10^{14} cm^{-2}, and 139 kΩ at 25 °C and 0.418 mΩ/G, 1.5×10^{14} cm^{-2} and 155 kΩ at 100 °C for Si and 5–10 mΩ/G, 6.25×10^{12} cm^{-2}, and 12 kΩ at 25 °C for pseudomorphic high electron mobility transistors (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 temperatures of 25, 100, and 125 °C for PHEMT, Si, and AlGaN/GaN 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. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3056172]

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 atomic force microscopy (AFM) feedback technique to be the one of the best choice as it provide means to perform sensitive, noninvasive, and quantitative imaging capabilities.[1] SHPM technique offers various advantages and complements the other magnetic imaging methods such as scanning superconducting quantum interference device microscopy,[2] magnetic force microscopy,[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 temperatures.

In this study we have investigated different kinds of heterostructures, AlGaN/GaN heterostructure, silicon-on-insulator (SOI), and pseudomorphic high electron mobility transistors (PHEMT) heterostructure, for their electrical and magnetic properties at variable temperatures (25–125 °C). In general two dimensional electron gas (2DEG) materials with high band gap (greater than 2.5 eV), such as 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, such as PHEMT, offers high response level and thus helps in increasing the sensitivity of the system. On the other hand due to complementary metal oxide semiconductor (CMOS) compatibility SOI structures have also been investigated for their application in Hall effect sensors.

The imaging capability of 1×1 μm^2 Hall probes from all three types of materials have been explored by scanning a hard disk sample for a temperature range of 25–125 °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 disk metal

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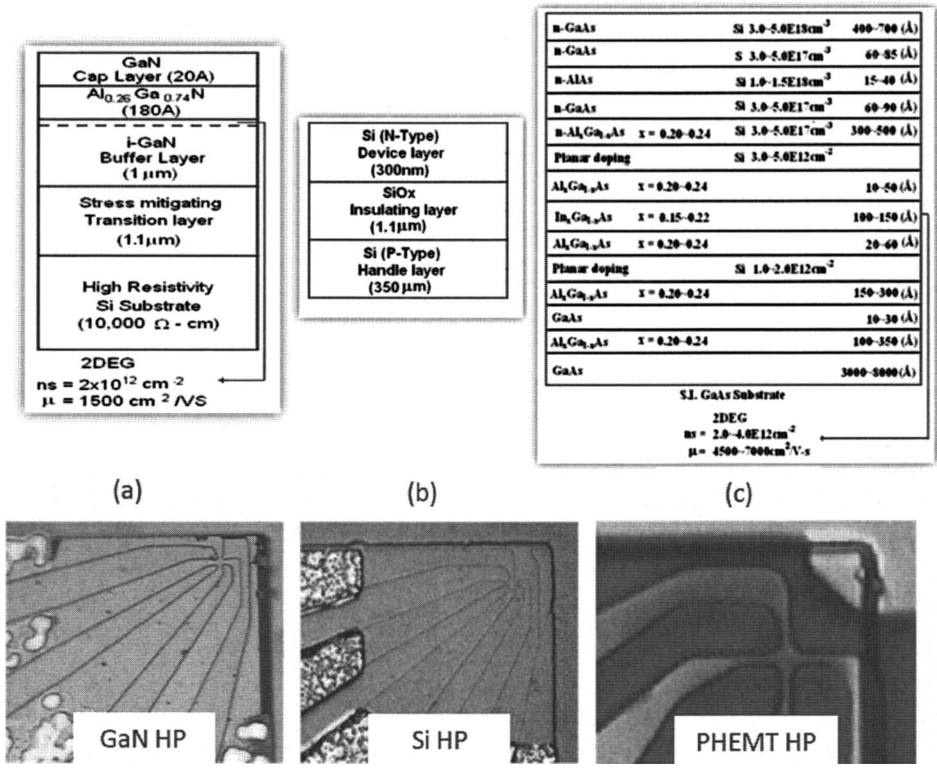

FIG. 1. Schematic of the layer configuration of the AlGaN/GaN heterostructure (a), SOI wafer (b), and PHEMT heterostruture (c), and corresponding photographs of 1×1 μm^2 Hall probes.

organic chemical vapor deposition material.[8] The epistructure of the wafer, as shown in Fig. 1(a), consists of the following layers: (1) a 20 Å thin layer of GaN cap layer for protection purposes, (2) 180 Å of $Al_{0.26}Ga_{0.74}N$ layer, (3) 1 μm thick layer of undoped GaN, which forms a 2DEG at the AlGaN interface, (4) proprietary stress mitigating transition layer of 1.1 μm, and (5) high resistivity Si (111) substrate with a resistivity of 10 kΩ cm. The room temperature sheet carrier concentration and electron mobility of the 2DEG induced at the heterointerface were 2×10^{12} cm^{-2} and 1500 cm^2/V s, respectively.

SOI wafer with thermal oxide has been used after thinning the device layer down to few hundreds of nanometers. The epistructure of the wafer, as shown in Fig. 1(b), consists of the following layers; (1) n-type device layer (2) thermal oxide SiO_x, and (3) p-type handle layer. The room temperature sheet carrier concentration was 2.2×10^{14} cm^{-2}.

PHEMT 2DEG semiconductor wafers used in this study were grown by molecular beam epitaxy on GaAs substrate. The epistructure of the wafer, as shown in Fig. 1(c), consists of the following layers: (1) cap layers for protection purposes with high doping concentration, (2) 2DEG structure, and (3) semi-insulating GaAs substrate. The room temperature sheet carrier concentration and electron mobility of the 2DEG induced at the heterointerface were $(2-4)\times 10^{12}$ cm^{-2} and 4500–7000 cm^2/V s, respectively.

2. Device fabrication

Micro-Hall probes with effective dimension of 1×1 μm^2 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. Device fabrication parameters are summarized in Table I.

Four Hall sensors are micro fabricated on a 5×5 mm^2 chip at a time and they are diced to a size of $1\times 1\times 0.5$ mm^3. 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 12 μm gold wire using an ultrasonic wire bonder.

B. Electrical and magnetic characterization

1. Electrical characteristics

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

Under high bias current conditions effect of temperature on V_H versus I_H characteristics can be quantified as a decrease in V_H for a particular current value. These percentage decreases are 31%, 44%, and 35% for GaN, Si, and PHEMT Hall probes, respectively, for a bias current of 500 μA. On

TABLE I. Device fabrication process and parameters.

Process	AlGaN/GaN	Si	PHEMT
Cap layer ETCH	⋯	⋯	Wet etch with H_2SO_4
MESA+recess	RIE with CCL_2F_2	RIE for Si with $SF6+O_2$ RIE for Si with $SF6+O_2$	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 30 s	400 °C for 30 s	⋯
Bonding metallization	Ti/Au	⋯	⋯
Bonding	12 μm gold wire	12 μm gold wire	12 μm gold wire

the other hand in the low current regime, GaN Hall probe shows an increase by 47% in the V_H versus I_H characteristics compared to decreases 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 hand, by increasing the current from 50 to 500 μA for a fixed temperature, increases in V_H versus I_H characteristics are 310% for 25 °C and 95% at 125 °C for GaN, but for Si these increases are 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, at any particular bias temperature condition, the value of r_H decreases by increasing the applied current from low current regime to high current regime. It is speculated that this decrease in the r_H value is due to the fact that there might be an opening of a 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 also been 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 versus I_H.

Similar comparison, as presented in the previous section, is summarized for magnetic characteristics in Table II. Based on these results we can say that PHEMT probes are the worse choice to be used for high temperature SHPM applications. Although Si shows 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.

During the experiments, the scanning sensor remains at high temperatures for long period of times. We have investigated run time effect on V_H versus I_H and R_H versus I_H characteristics under high temperature environments. The results showed no significant change in the values in case of GaN, while a decrease in 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.

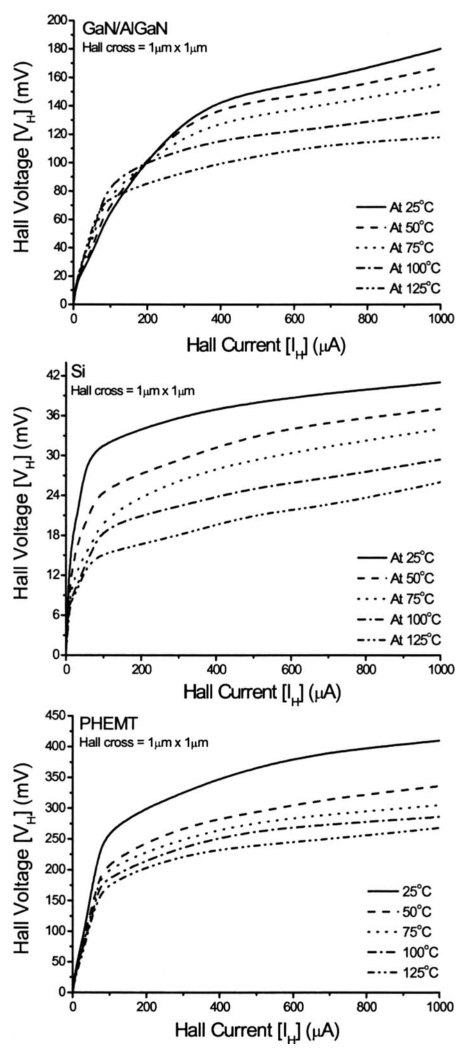

FIG. 2. Effect of temperature on the Hall voltage vs Hall current characteristics for all three types of micro-Hall probes.

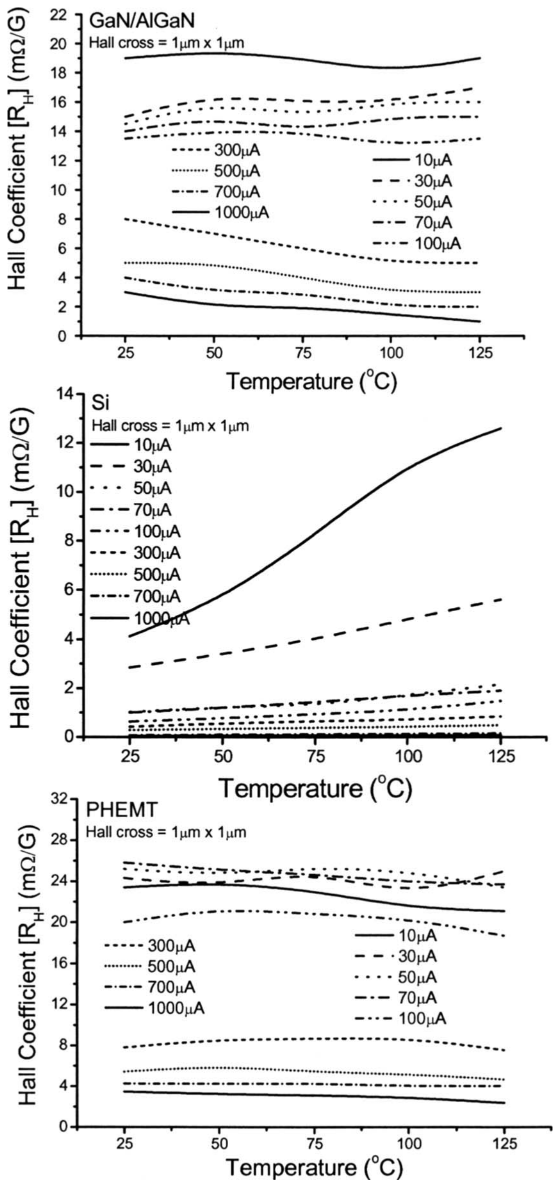

FIG. 3. Effect of Hall current on Hall coefficient vs temperature characterization of all three types of Hall probes.

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, scanning tunnel microscopy (STM) and AFM. As mentioned in Sec. I, in order to compensate the drawbacks of STM feedback especially at high temperature 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 nonmagnetic wiring. Furthermore these quartz tuning forks are glued to a 10×10 mm^2 printed circuit board sensor holder compatible with the scanning head of SHPM system. The Hall probe with chip size of $1 \times 1 \times 0.5$ mm^3 has been mounted on the quartz tuning fork using super glue. Figure 4 shows the assembly of the Hall probe on a quartz tuning fork. After mounting the Hall sensor chip with its bonding wire the resonance frequency of the tuning fork shifts from 32.76 to 10.1 kHz, 15.74, and 16.94 kHz for PHEMT, Si, and GaN Hall probes, respectively. The detailed analyses of the quartz tuning fork Hall probe microscope technique are presented somewhere else.[10]

TABLE II. Magnetic characteristics of Hall probes.

HP type/bias current (For a change in temperature from 25 to 125 °C)	50 μA	100 μA
AlGaN/GaN	10%↑	40%↓
Si	110%↑	75%↑
PHEMT	7%↓	14%↓
HP type/temperature (For a change in I_H from 50 to 500 μA)	25 °C	125 °C
AlGaN/GaN	190%↑	433%↑
Si	262%↑	337%↑
PHEMT	78%↓	80%↓

The Hall sensor is positioned 12 μm away from corner of a deep etch mesa, which serves as a crude AFM tip. The sample is tilted $\sim 1°-2°$ with respect to Hall probe chip ensuring that the corner of the mesa is the highest point. As the combined assembly of a sensor and tuning fork approaches the surface of the sample due to tip sample forces the resonant frequency of the quartz tuning fork shifts. The sensor assembly is dithered at the resonance frequency with

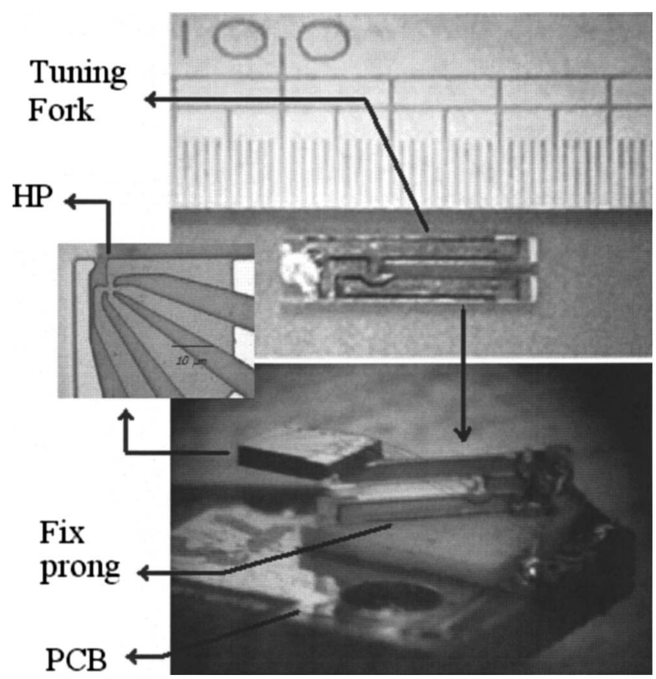

FIG. 4. Integration of micro-Hall probe with quartz tuning fork with gold wire for electrical contacts. One prong fixed to the base to reduce the noise and improve the resonance properties of the tuning fork (Ref. 10).

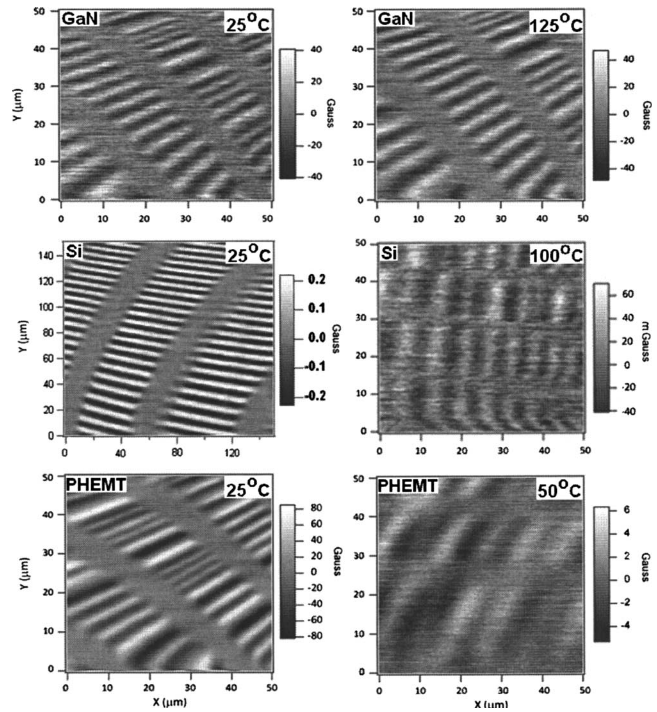

FIG. 5. SHPM image of hard disk sample at high temperatures. Scanning speed was 5 μm/s.

the dedicated split section on the scan piezotube 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) = 10 Hz. 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 of 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 500 μA dc, the series resistance of the Hall sensors were 9–12, 80–95, and 26–35 kΩ 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 low temperature system. The results of magnetic imaging of hard disk sample obtained in AFM tracking mode at 25–125 °C with a scanning speed of 5 μm/s and scan area of 50×50 μm^2 resolution of 256 $\times 256$ pixel shown in Fig. 5. 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 quartz tuning fork 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 are successfully used in scanning Hall probe microscopy. Electrical and magnetic characteristics of all three types of probes have shown a division of the characteristics, based on the bias current level at any particular biased temperature. A study of electrical and magnetic characteristics shows that GaN HP is a 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 25–125 °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 submicron devices and selection of other possible high temperature Hall probes are under investigation.

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