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Application of Scanning Hall Probe Microscopy Technique at Room Temperature 300K.

Hussein Ali Mohammed
Department of Physics, College of Education for Pure Science, University of Kirkuk, Kirkuk, Iraq.
hussein_ali722002@yahoo.com

Abstract

Active areas of bismuth Hall Probe sensors in the range (0.1 – 1) µm have been fabricated on Si/SiO_2 with GaAs substrates at thickness of bismuth from (40, 60 and 70) nm by Electron Beam Lithography (EBL) and lift-off process. Scanning Hall probe microscopy (SHPM) technique at room temperature (300) K used to study Hall voltage, characterization of the noise figures and minimum detectable fields. Results are presented for both 0.4µm sensor, which is found minimum detectable fields (B_{min}) ~1.1 G/ $Hz^{0.5}$ with dc currents about 5µA. But minimum detectable fields for HP size 0.6 µm at dc currents 20µA is B_{min}~0.6 G/$Hz^{0.5}$. The performance of our Hall probe devices at 300K could be improved still further are discussed.

Keywords: Bismuth hall probe devices, GaAs, Scanning hall probe microscopy technique.

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تطبيقات لتقنية المجهر النفقي الماسح عند درجة حرارة الغرفة 300 كلفن

حسين علي محمد

قسم الفيزياء، كليةالتربية للعلوم الصرفة، جامعة كركوك، كركوك، العراق.

hussein_ali722002@yahoo.com

الملخص

المساحة الفعالة لنماذج مجس البزموث النفقي وبقياسات تتراوح ما بين µm (0.1−1) وتم تحضيرها على اساس مواد كل من (Si/Sio_2) , (GaAs) وبسمك nm (70,60,40) بواسطة تقنية شعاع الالكترون (EBL) مع عملية (lift−off) . تم استخدام تقنية المجهر النفقي الماسح (SHPM) عند درجة الحرارة الغرفة لدراسة فولطية المجس النفقي مع خصائص اشكال الضوضاء لأدنى مجالات مغناطسية ممكن كشفه . والنتائج تتمثل لنموذج 0.4µm ووجدت ادنى مجال مغناطيسي ($B(min)=1.1\ G/H_Z^{0.5}$) مع تيار مستمر 5µA. ولكن بالنسبة لنموذج 0.6µm فان ادنى مجال مغناطيسي بحدود ($B(min)=0.6\ G/H_Z^{0.5}$) مع تيار مستمر بحدود 20µA . وتم مناقشة تحسن اداء المجس النفقي الماسح عند درجة الحرارة الغرفة .

الكلمات الدالة: مجس البزموث النفقي، مركب الزرنيخ، تقنية المجهر النفقي الماسح.

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1. Introduction

Scanning Probe Microscopy technique (SPM) [1, 2] is a new technique at room temperature must operate effectively. Scanning Hall probe microscopy is best part of it which has high spatial resolution of sensors as well as nanoscale sizes are fabricated and worked in close to surface of active area. Bismuth is a semi-metal with low effective mass, low carrier density, and long mean free path .The carrier density with mobility of Bismuth are very important to find the figure of merit [3]. Bismuth is much, or suited for room temperature operation than GaAs/AlGaAs . Also one-over-of noise is a fluctuation in the conductivity which leads to fluctuation in the resistance then leads to slow fluctuations in the power density of the thermal noise [4]. But it has disadvantage which that the carrier density rely on a figure of features such as thickness of film, quality of substrate material and deposition technique. In practice, fabrication by scanning bismuth active areas have been broadly examined. Nanoscale of active areas about ~50 nm but Focussed Ion Beam (FIB) technique used for larger hall probe. Currently, we are used lift-off fabrication in order to get very low noise in bismuth hall devices to improved figures of merit such as minimum detectable fields, Hall coefficient (low carrier density), Johnson noise, 1/f noise and low offset resistances [5]. In this work was extended here to use EBL technique with scanning bismuth Hall probe devices which active areas have range (0.1 to 1) µm.

2. Experiment

This fabrication of Bi-Hall Probe sensors was performed at Bath University Nano-fabrication Lab “clean room facility”.Si/SiO_2 and GaAs substrates wafers were scribed and cleaved into (6.5 x6.5) mm squares ‘chips’ using a diamond scribe. The chosen size was considered suitable for package and it is enough for Ohmic contact size. Once the devices were fabricated, the Si/SiO_2 and GaAs substrate (6×6) mm squares were scribed into bigger (7 ×7) mm or (6.5×6.5) mm chip. Samples were cleaned in an ultrasonic bath in solutions of trichloroethylene, acetone and isopropanol correspondingly. The samples are soaked in chlorobenzene for four minutes so as to make the top layer. The sample and mask (using a Karl Suss MJB3 mask aligner) must be very clean before starting. Best exposure time about 12-22 seconds. Throughout-the procedure care must be taken to ensure that there is a gap between sample and mask.

The researcher should look for coloured interference fringes between the sample and the mask where the spacing is roughly the order of the wavelength of light in magnitude. Sometimes fringes are never seen - in which case resist blotches near the corners of the chip or signs that the chrome mask is being deformed upwards due to contact with the chip near the chip corners. If this is seen, the sample must not be raised any closer to the mask. This mask is brought into close contact with the coated substrate and illuminated with UV light, which passes through the transparent areas and weakens the bound in the resist. In order to get high quality samples, it is required that any contamination is removed. Contamination is caused by particles from several things such as air and previous processing steps [4]. The exposed samples are developed using 351 developer (in the ratio of H_2O: Developer 3.5:1) for a duration of 30-50 seconds. After this period above immediately soak them in beaker of water for a period of around 10—15 seconds, in order to rinse and dry then using a nitrogen gun.

EBL technique is excellent for making best designs required by the up-to-date with electronics devices for integrated circuits. It has very small spot size of the electrons, as well as the quality of resolution in lithography material is best determination by the wavelength of exposure light device. See Fig. 1.

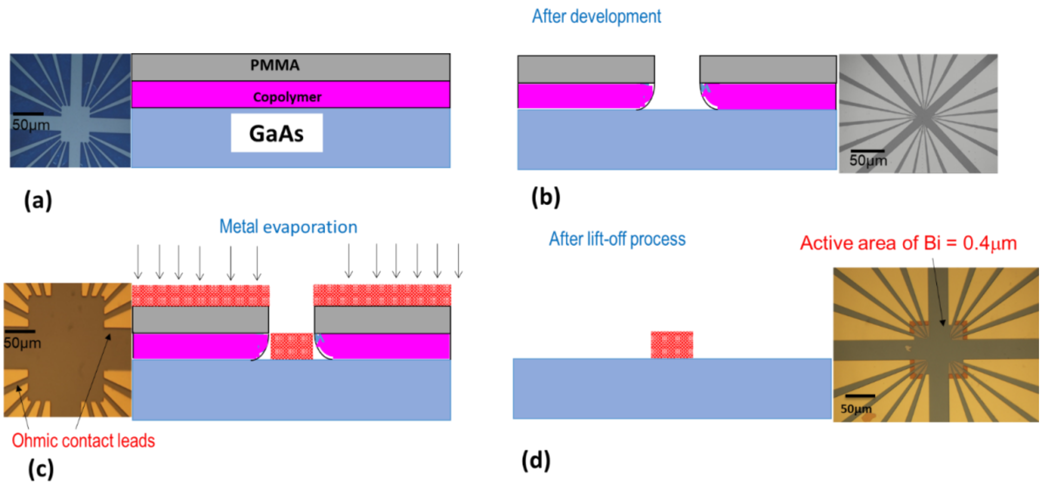

Fig. 1: The Electron Beam Lithography (EBL) with Bi deposition. Shows many stages of Bi-HP fabrication as follows: (a) - The samples are covered by photo resist S1813 and are exposed by UV light. (b) –Ohmic Contact of samples deposited by 10nm Cr / 50nm Au.(c)–EBL for Bi-HP design and deposited by 70 nm of Bi.(d)- deposited especially Ohmic Contact by 20 nm Cr / 200 nm Au.

These chips (10×10) mm were glued by epoxy onto alumina packages. The wire Au 25 µm contacts on the sample is bounded as well as wires of Cu is longer than Au. Chips has sixteen terminals from the plate contact of sample. Scanning electron microscopy (SEM) images of 0.1 µm Hall probe size (HP) as shown in Fig .2.

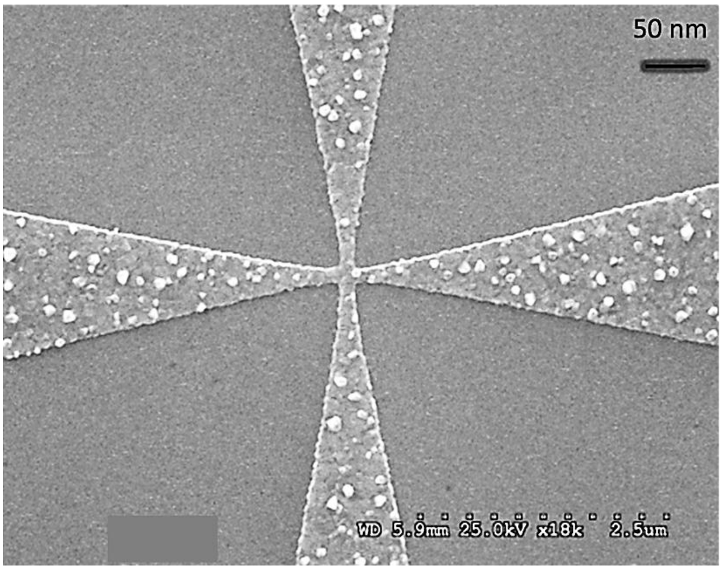

Fig. 2: Images for SEM technique of 0.1 µm Hall probe size with 70 nm thick Bi-Hall probe device.

3. Results and Discussion

The main goal in this article is the study of Bismuth micro-Hall probe sensors with a wide range of sizes (0.1 -1) µm at room temperature (300K). All results obtain for some size of Bi-Hall probe such as 0.6µm and 0.4µm. Measurements have been made on 8 groups of Bi-HP samples and each group has at least 5-7 samples. All eight experiments were conducted over one year and obtained good results have been obtained for both the 0.4µm and 0.6µm devices utilising Scanning Hall Probe Microscopy. The Hall voltage signal was measured by lock in amplifier and suing Oxford Cryogenics Instruments Ltd cryostat. The calibration of in –plane field coil is 105.62 G/A with the calibration of out-of-plane field coil is 1.7 G/A. For width 0.6 µm of Bi-HP at room temperature which has thickness~ 70nm , the offset resistance is 2.7Ω, when B=0 and the Johnson noise of the Bi-HP about ~ 10 nv/ $Hz^{0.5}$ when maximum current of hall around 20µA and minimum detectable fields B_{min}~0.6 G/$Hz^{0.5}$. The Hall

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coefficient (R_H) is 8.3 Ω /G and series resistance (Rs) of the Bismuth hall probe about 6 KΩ. See Fig. 3.

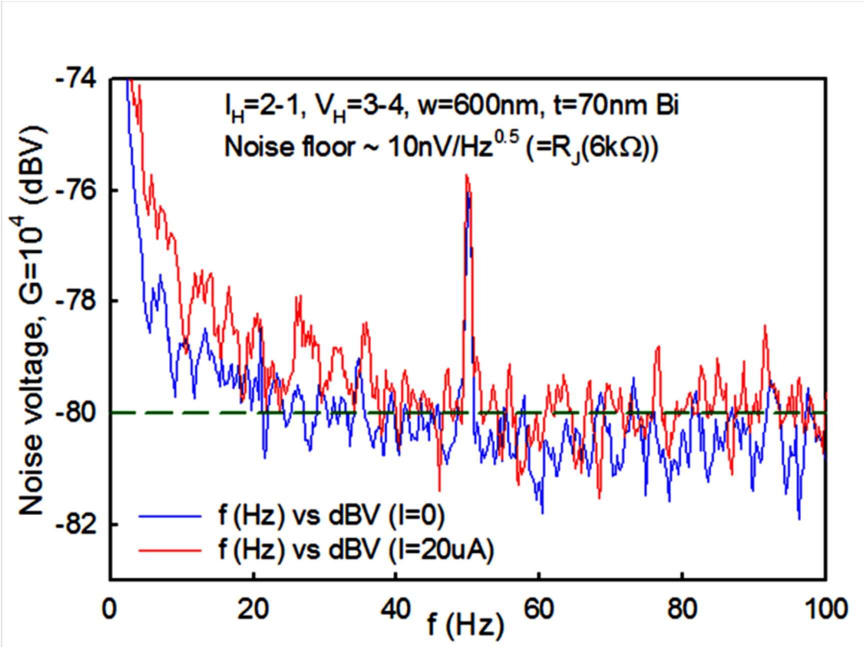

Fig. 3: Noise spectral density versus frequency for the Bi-HP measured. HP, width (w) =0.6 µm, thickness (t) =70nm of Bi, and T=300K.

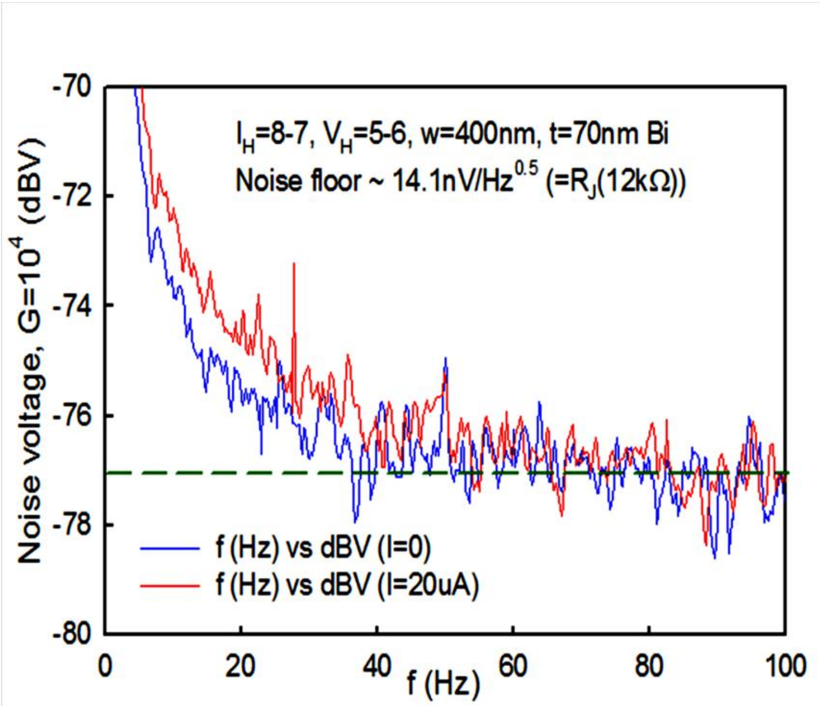

Fig. 4 Noise spectral density versus frequency for the Bi-HP measured. HP, width (w) =0.4 µm, thickness (t) =70 nm Bi, and T=300K.

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Fig.4. Shows 0.4μm Bi-Hall probes at 300K with same Hall current. The data displays a 1.9Ω offset when B=0 with 14.1 nv/ $Hz^{0.5}$ for Noise floor and minimum detectable fields B_{min}~1.1 G/ $Hz^{0.5}$. The Hall coefficient (R_H) is 6.2 Ω /G and series resistance (Rs) of the Bi-HP around 12kΩ. The noise data is taken one hundred times for each sampling. It is noticeable that, the bandwidth of both Bi-HP 0.4μm and 0.6 μm is 954.85 mHz and frequency of spectrum noise is ranged between (0 – 100)Hz with (100 rms). The noise level in Fig.3 decreased at - 74 $\times 10^4$ (dBV) gradually with frequency until it reaches to corner of spectrum noise which is called (one-over-of) noise which is the minimum noise threshold of this 0.6μm Bi-HP device. The frequency semi stable at range (20-100) Hz then it called white noise. But for the 0.4μm Bi-HP sample, the noise level decreases from -70 $\times 10^4$ (dBV) and range of white noise is around (30–100) Hz as shown in Fig.4. The reason for using a Bi-Hall probe at room temperatures (300K) rather than a Hall-probe GaAs/ AlGaAs heterostructure is that the signal noise ratio of GaAs/ AlGaAs is poor.

Where, for a given field, temperature and Hall probe dimensions (width/length) the signal noise ratio (SNR) are three parameters such as current Hall probe (I_{Hall}), mobility (μ) and carrier density (n)for two dimensions in which mobility does not change much with temperature for Bi. Nevertheless, changes many orders of magnitude with temperature for GaAs 2DEGs and the (n2d) for Bi is given by (n3d × d), where d is the thickness of the Bi film. Table 1 shows an answer to the question as to why (Bi) is better than GaAs/AlGaAs at 300K. For Bi-Hall probe is four times bigger than GaAs/AlGaAs. The maximum value of (I_{Hall}) for Bi is probably >10 μA at all temperatures, while for GaAs it is 1 μA at 300K and (10-40) μA at 77K.

Table 1: Shows comparison between Bi Hall probe with GaAs/AlGaAs hetero structure at 300K.

Parameters	Bismuth (Bi) at room-temperature (300K).	GaAs/AlGaAs Heterostructure at room-temperature (300K).
Maximum value of Hall current(I_{Hall})	>100 μA.	1 μA.
Mobility(μ)	200 $Cm\ V^{-1}\ S^{-1}$	1000 $Cm\ V^{-1}\ S^{-1}$
Carrier density for two dimensions ($n2d$)	$8\times 10^{1}\ Cm^{-2}$	$2 \times 10^{12}\ Cm^{-2}$
Signal-to-noise ratio (SNR)	32×10^{-5}	7×10^{-5}
Hall coefficient (R_H)	8×10^{-4} Ω /G	0.3 Ω /G

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Hall sensors device of Sub-micrometre (GaAs/AlGaAs) are more suitable for 4K (low temperature) which has measurements with very high spatial resolution than Bi-HP because GaAs/AlGaAs Hall sensors is bigger signal-to-noise ratio (SNR) with Hall current (I_{Hall}) than Bi-HP. However, Bi-Hall probe sensors (Bi-HP) are suitable for room temperature 300K than GaAs/AlGaAs for same reasons. Noise spectra shows in figure 6 several hall currents for active areas 0.1µm GaAs/AlGaAs sub-micro in a width 0.4µm of Bi film. Dash line flat in figure indicates the high frequency Johnson noise floor, corresponding to a voltage lead pair resistance of 3.1 kΩ, nearly with the value 3.4 kΩ . Obviously the little frequency noise produces rapidly with the 1/f shoulder and Hall current. Fig. 5 shows shifts of higher frequency, increasing above our frequencies measurement at I_H=30 µA.

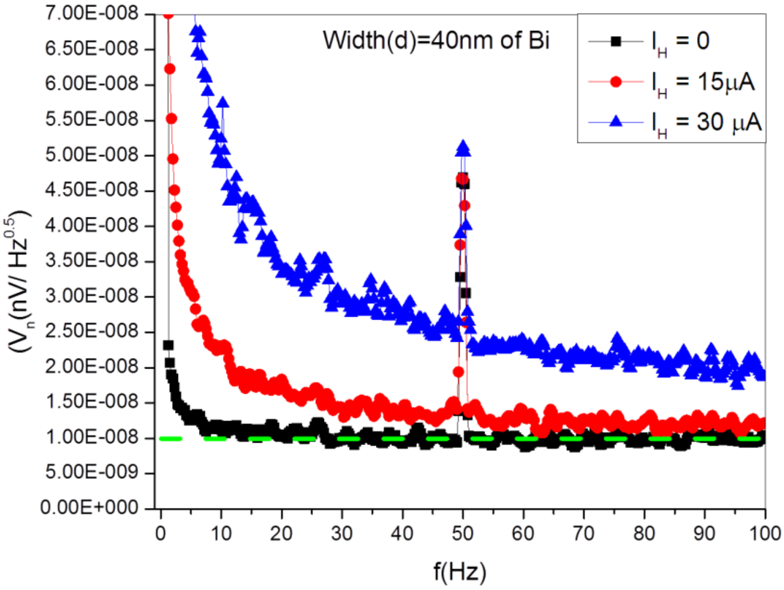

Fig. 5: Noise spectral concentration, V_n, shows a frequency function of 0.1um bismuth Hall probe size at room temperature**.**

The minimum detectable field (B_{min},) is important figures of merit for hall active areas and defined approximated by: [6]

$$B_{\min} = \frac{\sqrt{4R_V k_B T\Delta f}}{I_H R_H} \qquad (1)$$

Where I_H is the applied Hall current, R_H is the Hall coefficient B is the magnetic field.

K = Boltzmann constant (1.38×10^{-23} Joules/Kelvin).

Δf = the measurement bandwidth in Hz.

T= Temperature in degrees Kelvin (K = +273 Celsius),

The minimum detectable field in Fig. 6 demonstrations plotted as function of Hall active size for several width. The smaller Hall probes chiefs to a quick increase in the minimum detectable field. Hall active area for 1µm has minimum detectable fields ~0.1mT/$Hz^{0.5}$ with hall currents about 70 µA.

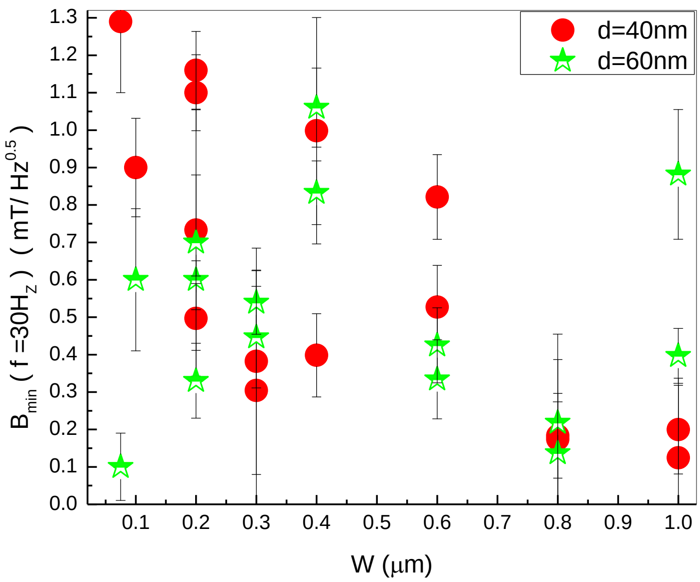

Fig. 6: Minimum detectable fields as a function of Bi-HP sensors fabricated in 40nm and 60nm thick.

Three a strong function of hall coefficient of Bi hall probe are quality of substrate material, thickness of thin film and deposition technique [7]. The hall coefficients of active area is 1.81Ω/T measured from 40nm thick of bismuth size area nevertheless for (60nm) thick Bi films sensors is 0.85Ω/T. Both Sandhu *et al* and Petit *et al* found R_H=4.0 Ω/T in a 50nm hall probe fabricated by FIB technique in a 60nm Bi film deposited on GaAs substrate as well as for 750nm hall probe R_H=1.73 Ω/T used same technique in a 78nm thick of Bismuth films respectively [8,9].

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Our smallest Hall probe sensors at 300K has minimum detectable fields from (10 to 80) $\mu T/Hz^{0.5}$ for 0.1µm sensors and hall currents around (5-40) µA. Sandhu found 70 $\mu T/Hz^{0.5}$ in Bi the 50nm probes but Petit found 5.1 $\mu T/Hz^{0.5}$ for the active area of Bismuth hall probes 750nm thickness [8,9]. In order to find minimum detectable fields so the best way is measuring the spectral noise density. Spectrum noise Figures attention at (30 Hz) in size 0.1 µm devices for 50nm sub-bismuth hall probe films thickness which it has B_{min}=0.9mT/$Hz^{0.5}$ with a 5µA Hall current. Both 200nm and 300nm sub-micro sensors using larger current to measure minimum detectable field reduced to 0.5mT/$Hz^{0.5}$ and 0.3mT/$Hz^{0.5}$ for 0.3µm films. Noise spectra measured of 78nm Bi films by FIB technique as a function which is report by Petit *et al*. [10].

As a final point, our microstructure of Bi-HP sensors can be improved to complete best figures of merit. Sandhu *et al*.[8] used evaporated for Bi-HP sensors at very high deposition rates subsequently found a much higher Hall coefficient in films. Nanoscale has currently been demonstrated bismuth hall probe films deposited on oxidised Si substrates leads to smoother surface of Bi-HP films [11].

4. Conclusions

Bismuth hall probe films fabricated at 300K using lift off process and EBL techniques with active areas from (0.1 -1) µm. Properties of Bismuth micro-Hall probe sensors for different active widths were studied. However, results showed for two sizes (0.4 and 0.6) µm that the Johnson noise of the Bi-HP about ~ 14 nv/ $Hz^{0.5}$ and 10 nv/ $Hz^{0.5}$ respectively at maximum driving Hall current of 20 µA .The spectrum noise (1/f noise) corner is around (0 - 20) Hz but, range of noise continues to increase to large frequencies. The Hall coefficient (R_H) for width 0.6 µm of Bi-HP at room temperature is 0.8 Ω /T and the Hall coefficient (R_H) for 0.4um Bi-Hall probes is 6.2 Ω /T. Bismuth is much, or suited for room temperature operation than GaAs/AlGaAs. Because, it has much lower carrier mobility at room temperature leads to much higher lead resistances and Johnson noise, and dramatically increases minimum detectable fields.

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