Anomalous Hall Effect in Nickel Thin Film at Low Temperatures

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Abstract. In this paper we report the observation of Anomalous Hall Effect (AHE) in the well characterized Nickel thin film of ~ 17 nm thickness. Thin film of Nickel is grown on Silicon (100) substrate using metal evaporation unit and characterized by XRD and XRR measurements. Nickel being ferromagnetic below 627K shows the contribution of both ordinary hall resistivity (due Lorentz force from applied magnetic field) as well as anomalous hall resistivity (due to spontaneous magnetization). Anomalous hall resistivity increases with temperature in the observed temperature range of (10-150K) showing the scaling with longitudinal resistivity of metallic behavior of Nickel.

INTRODUCTION

Hall Effect and resistivity are important techniques for studying thetransport properties in solids. Hall Effect is a direct manifestation of Lorentz force on the free electrons inthe solids discovered by Edwin Hall in 1879. One year later extra ordinary contribution of Hall was discovered in magnetic materials by Edwin Hall again in 1880.The Hall resistivity of ferromagnetic materials can be expressed as $\rho_{xy}= R_oB+4\pi R_sM$, where the first term is ordinary Hall resistivity and the second term is Anomalous Hall resistivity which is proportional to the spontaneous magnetization. The Anomalous Hall effect (AHE) in ferromagnetic material has attracted extensive attention due to its application in spintronic devices [1,2]. The origin of AHE may have intrinsic or extrinsic (skew- scattering and side jump) mechanisms. Extrinsic mechanisms are attributed to impurity scattering in the presence of spin- orbit coupling (SOC) [1]. Nickel has a ferromagnetic transition at the Curie temperature (T_C) of 627K. Recently Guo et al.,had observed AHE dominated by skew- scattering mechanism in 7-15nm of Nickel films at 5K whereas in 40- 200nm of Ni films AHE was shown to be dominated by side jump mechanism [3]. The ultra-thinfilmsof 4nm and 6nmshow the suppression ofhall resistivity with increase in temperature, because surface scattering decreases in ultra-thin films due to decrease in mean free path on increasing the temperature [3].The Planar Hall resistivity was observed by Chen et al. in Ni thin films which is mainly contributed by extraordinary part of magneto-resistivity in single crystalline Nickel film [4].The Hall resistivity decreases with increase in film thickness of Nickel [3,5,6].Also, the deposition temperature of films affects the hall voltage. An increase in deposition temperature makesthe film more metallic because of growth of bigger crystallites and such films have lesser grain boundaries which decreases the transverse resistance of film thereby decreasing the hall voltage. In this manuscript we report the preparation, characterization and observation of Anomalous Hall effect in the ferromagnetic region.

EXPERIMENTAL DETAILS

Thin film of Ni is deposited on Silicon (100) substrate using thermal evaporation technique. Initially the substrate is heated upto 200^{o}C and then the deposition process is continued for few minutes on the rotating substrate. After deposition the film was annealed for ~ 3 hours at 200^{o}C. During the deposition the sample chamber was maintained at 6 x 10^{-7} torr of vacuum. The X-ray diffraction of film was done on Bruker-D8 Advance Diffractometer (Cu-k_α, λ= 1.54) and the X-ray Reflectivity was done in Bruker-8 Discover Diffractometer. Hall measurements are done by five probe method on the9T-PPMS, in the temperature range of 10-150 K andup to 3T magnetic field. Five probe method is best suited for hall measurements for metallic materials.

RESULTS AND DISCUSSION

FIGURE 1(a) shows the X-Ray diffraction of prepared thin film in which the peaks are observed at 44.4^0 and $\sim 52^0$ (matched with powder diffraction file no. 870712for Nickel) and absence of any extra peaks suggests the deposited film is single phase in nature and is a pure Ni film having no impurities present. The data on the top (blue curve) is for Ni/Si(100) whereas data below (red curve) is for Si(100). The peaks are identified and are marked as S and F for the Si(100) substrate and Ni film respectively. **FIGURE 1(b)**shows the X-ray Reflectivity pattern of deposited film which is fitted by Parratt software. The fitting parameters obtained from the XRR data gives the thickness of the film to be ~17nm.

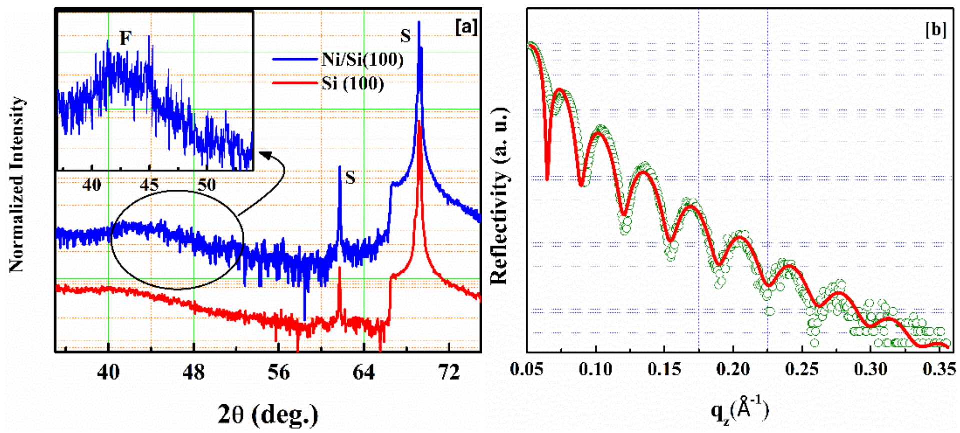

FIGURE 1: (a) X-Ray diffraction data of Ni/Si(100) [Blue line]. The Red colored line shows the data for Si (100) substrate. The inset shows the zoomed view indicating the peak corresponding to Ni.(b) X-ray reflectivity of Nickel film. Green open circles show observed data and red line shows the fitted model.

The **FIGURE 2** shows the isothermal hall resistivity as a function of magnetic field and at different constant temperatures. It is seen that the hall resistivity increases steeply with increasing magnetic fields upto 0.2 T. This sharp increase of hall resistivity at low fields is the well-established extraordinary/anomalous Hall Effect observed in ferromagnetic systems. The anomalous hall response is due to the development of spontaneous magnetization in the sample. The anomalous hall resistivity (AHR) can be observed even in the absence of external magnetic field (H). The overall hall resistivity can be empirically written as $\rho_{xy}= R_oB + 4\pi R_sM$, where R_0represents the ordinary hall coefficient and Rs is extraordinary/anomalous hall coefficient which is proportional to the magnetization (M). The saturation shown in graphs in **FIGURE 2**, at all observed temperatures is an indication of anomalous part. The measurement temperatures are 10K, 20K, 40K, 60K, 80K, 100K, 125K and150K which are well below the Curie temperature of Nickel (627K) and hence our film is in the ferromagnetic state at these measured temperatures. The anomalous part in the hall resistivity is found by extrapolating the high field (well above saturation field which is 0.2T in our case) hall resistivity data to zero field. The anomalous hall resistivity is ~ (-1.69) x $10^{-7}\mu\Omega$ cm at 150 K and ~(-1.26) x 10^{-7} $\mu\Omega$ cm at 10 K, whereas the ordinary hall resistivity is~ (-4.36) x 10^{-13} $\mu\Omega$ cmand (-3.22) x 10^{-13} $\mu\Omega$ cm.The anomalous Hall resistivity is almost five orders larger than the ordinary hall resistivity in our film.The negative slope of the ordinary hall resistivity indicates that electrons are the majoritycharge carriers in the measured temperature range.

Magnetism has a profound influence on the transport properties like resistivity and Hall Effect. The origin of the anomalous Hall Effect has remained ununderstood since long and various theories have been proposed for the mechanism behind the anomalous hall resistivity. Karplus and Luttinger theory proposed in 1954, considered the band structure in ferromagnetic materials but completely ignored the scattering process from disorders, whereas Smit in 1958 suggested the scattering of electrons by lattice imperfections along with Spin orbit interactions are responsible for AHE , hence skew scattering of conduction electrons was the mechanism suggested for AHE [7,8].

In 1970, Berger suggested the extrinsic side jump mechanism responsible for AHE [9]. The underlying origin could be either domination of intrinsic mechanism, skew scattering or side jump mechanism. This can be found by the proper scaling of the anomalous hall resistivity with the longitudinal resistivity which is required for understanding the mechanism behind AHE in the present thin film. We have calculated the anomalous hall resistivity at the highest measured field of 3T at all the observed temperatures below 150K and is plotted as a function of temperature in **FIGURE 3**. The gradual rise in the Hall resistivity (ρ_{xy}) with temperature indicates that the hall resistivity scales with the longitudinal resistivity of metallic Nickel films. The scaling of AHR with longitudinal resistivity would reveal the scattering mechanism responsible for AHE.

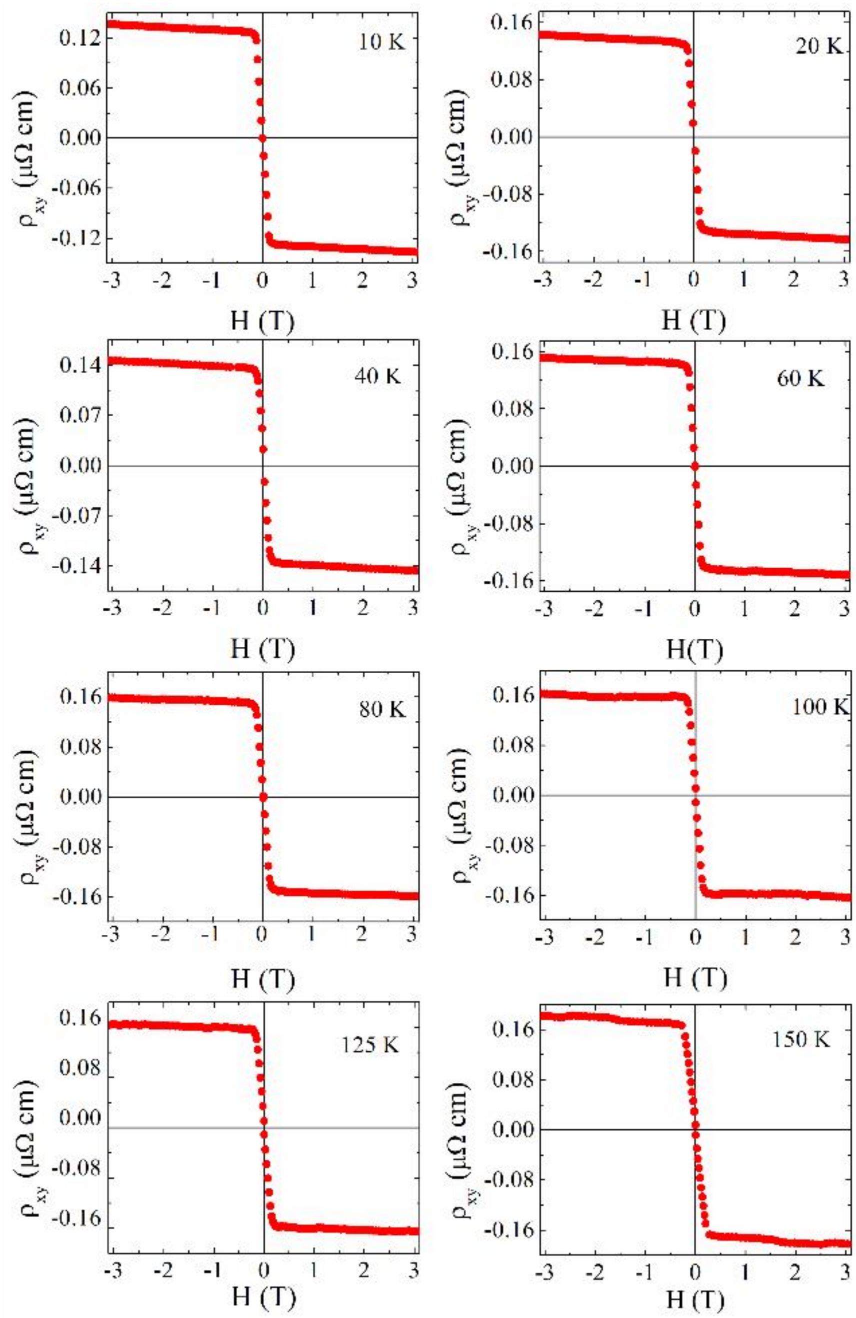

FIGURE 3: Isothermal Hall resistivity data of Nickel film measured at various fixed temperatures.

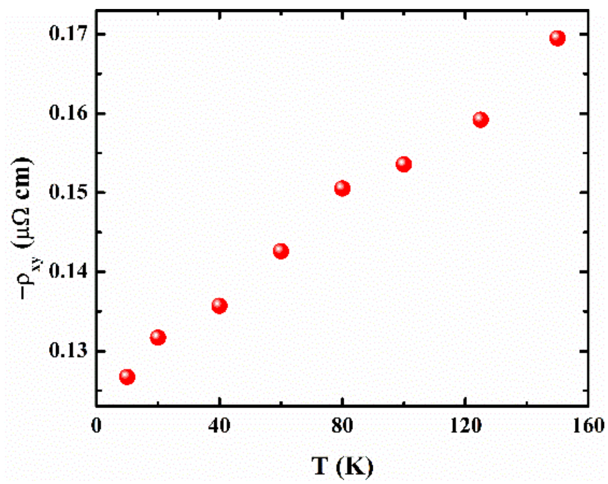

FIGURE 4: Temperature dependence of Anomalous Hall resistivity of Nickel film.

CONCLUSION

Polycrystalline thin film of Nickel is deposited on Silicon(100) substrate using thermal evaporation technique. XRD and XRR measurements are used to characterize the film, which confirm the single-phase formation of Nickel film having ~17nm thickness. Anomalous HallEffect (AHE) is observed inthe temperature range of study below the Curie temperature The gradual rise in AHR as a function of temperature in the range 10K – 150K, demonstrates the scaling with longitudinal resistivity.

ACKNOWLEDGMENTS

Authors thank Dr. M. Gupta and Er. L. Behera for XRD measurements, Dr. V. R. Reddy and Er. A. Gome for XRR measurements. Dr. A. K. Sinha and Dr. V. Ganesan are acknowledged forsupport and encouragement.

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