SK2822 Hall Effect Lab Report

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***Abstract*—Hall effect measurements were carried out on thin film layers of GaAs and $GaAs_{0.75}P_{0.25}$ with two different substrates (semi-insulating GaAs, GaP) and at temperatures of 295K, 77K using Van der Pauw technique; and the effect of layer composition, measurement temperature were noted. Hall voltage (V_H) was measured to observe the aforementioned effects by deriving – hall mobility (μ_H), carrier concentration (n/p) and hence the layer type ($n-$ or $p-$).**

I. Introduction

It is well known from Maxwell's equations that charge carriers in an electric field (**E**) curl perpendicularly upon the application of a mutually perpendicular magnetic field (**B**), and this effect was first observed in a thin gold leaf by Edwin Hall; wherein longitudinal current carrying charges in a material (conducting or semi-conducting) curl towards the lateral edges under the influence of a lateral **B** giving rise to a transverse hall voltage (V_H). The hall resistance (R), which is the ratio of V_H created to the amount of longitudinal current (I) supplied under a lateral **B**, is a characteristic constant for a particular material. And at sufficiently low temperatures and large **B**, R becomes quantized at integral or even fractional values depending on the material's respective filled band Chern number summations.

A. Theory

Relevant equations for Hall effect in a material include –

1) Expression for Hall Coefficient (R_H): Equating transverse forces on a negative charge (alternatively a positive charge) in the material along y under B_z, E_x and induced E_y

$$eE_y = \mp r \cdot e(\boldsymbol{v} \times \boldsymbol{B})_y = \pm r \cdot ev_xB_z = \mp r \cdot \frac{eB_zj_x}{ne}$$

$$\text{Thus, } R_H = \frac{E_y}{j_xB} = \mp r \cdot \frac{1}{ne} \tag{I-A.1}$$

Here, the hall factor r is a material constant.

2) Expression for Hall Mobility (μ_H): From the expression of charge drift velocity under longitudinal E_x and lateral B_z

$$\begin{gathered} v_x = \mu E_x \\ \mp\frac{r}{ne} = \mu \cdot \frac{V_x}{Lj_x} \\ \Rightarrow \text{From I-A.1, } R_H = \mu\rho \\ \text{And } \because \mu \approx \mu_H \forall B_z, \ \therefore \mu_H = \frac{|R_H|}{\rho} \end{gathered} \tag{I-A.2}$$

3) Expression for Hall Voltage (V_H) along y of transverse cross section $d \times d$: From I-A.1

$$\begin{gathered} eE_y = \pm\frac{r}{ne} \cdot e(\boldsymbol{j} \times \boldsymbol{B})_y = \mp\frac{r}{ne} \cdot eB_zj_x \\ \Rightarrow \text{From I-A.2, } E_y = R_H \cdot B_zj_x = \mu_H\rho \cdot B_zj_x \\ \therefore V_H = E_yd = \mu_H\rho B_z\frac{i_x}{d} = R_HB_z\frac{i_x}{d} \end{gathered} \tag{I-A.3}$$

B. Applied equations for the hall measurements

From I-A.3,

$$R_H = \frac{V_H}{i_x}\frac{d}{B_z} = R \cdot \frac{d}{B_z} \tag{I-B.1}$$

where, R is the measured hall resistance through V_H and i_x.

For a better accuracy for R_H measurement, the four-point Van der Pauw technique with both directions of V_H, i_x and B_z was used to account for the material's asymmetry. Thus, averaging the 8 different permutations of i_x, V_H and B_z; R can be modified as –

$$\begin{aligned} R = \frac{1}{8}\Big[&R_{31,42}(+B_z) - R_{13,42}(+B_z) + R_{42,13}(+B_z) \\ &- R_{24,13}(+B_z) + R_{13,42}(-B_z) - R_{31,42}(-B_z) \\ &+ R_{24,13}(-B_z) - R_{42,13}(-B_z)\Big] \\ \text{And, } &\because \rho = R \cdot d \\ &\therefore \text{ From I-B.1, } R_H = \frac{\rho}{B_z} \end{aligned} \tag{I-B.2}$$

Thus, just by knowing d and B_z, and by measuring R_H in the way mentioned in I-B.2; the material's μ_H (from I-A.2) and carrier concentration (from I-A.1) can be derived.

II. Experimental Work

Hall effect was measured on various samples at temperatures (T) 77K and 295K, each consisting a square areal (predetermined cross-section) thin film of 7.5μm thickness grown on either semi-insulating GaAs or GaP substrate. The thin films were chosen to be square areal ($d \times d$) to ensure that symmetry factor (Q) of the thin film is low enough for negligible influence on the film's resistive measurements. And to compare the effects of layer composition, measurement temperature and substrate composition; the following thin films were studied upon – sulphur-doped GaAs and sulphur-doped $GaAs_{0.75}P_{0.25}$.

Experimental procedure for the hall measurement include –

1) Sample Contacting: Indium point contact dots were placed manually close to (but not at) the four corners of each sample, to ensure negligible edge effects due to material discontinuity during the Van der Pauw measurements. Indium was specifically chosen as the material for point contact because of its ohmic nature (linear I-V with low contact resistance), low schottky barrier with the thin film and ease of handling (high malleability). And finally, the Indium contacts dots were made point-sized w.r.t to the sample size to ensure smaller deviations in V_H measurements.
2) Sample Annealing: Having positioned the contact dots, the samples was annealed in a nitrogen ambient furnace for 90 seconds at a low thermal budget of 653K. Any higher temperature would result in the segregation of III and V group elements in the sample, because of the sample composition reaching its miscibility gap.
3) Sample calibration: The sample is then mounted on the hall apparatus with a probe station for measurements. Point contacts are checked to be ohmic by monitoring the sample's contact resistance deviations under varying currents. And depending on whether the resistance is too high or too low, a constant voltage or a constant current measurement is employed later for the hall experiment. A configuration file capturing inputs (B_z, d, experimental temperature and constant I or V) for the hall experiment is loaded onto the hall apparatus.
4) Hall measurement: The sample's contact resistance is rechecked, and then as described in I-B.2 all permutations of i_x, V_H and B_z are carried out to accurately measure the thin film's ρ, μ_H, carrier concentration (n/p) and symmetry factor ($Q = R_{\text{longitudinal}}/R_{\text{transverse}}$).

Considerations for the hall characterisation setup include –

1) A thick enough semi-insulating substrate (GaAs or GaP) for the thin film layer on which hall effect is to be measured, to account for the depletion region thickness so that electrical thickness is still available for current conduction, and to make sure of negligible current conduction through the substrate during hall measurement.
2) The choice of an electrometer or a high impedance buffer over a nanovoltmeter, to characterise a wider range of layer resistivities ($10^{-4} - 10^{9}\ \Omega \cdot cm$) in the Van der Pauw technique.

III. Results and Discussion

TABLE III-.1: Hall Measurements at $|B_z| \approx 4kG$

Thin Film Parameters	GaAs/SI−GaAs at 77K	GaAs/SI−GaAs at 295K	$GaAs_{0.75}P_{0.25}$/SI−GaAs at 295K	$GaAs_{0.75}P_{0.25}$/GaP at 295K
ρ ($\Omega \cdot cm$)	1.6720	3.9221	0.0234	0.0199
μ_H (cm^2/Vs)	9282.4619	3883.6835	1049.5882	1216.6829
n/p (cm^{-3})	4.02699×10^{14}	4.10315×10^{14}	2.54475×10^{17}	2.58137×10^{17}
Q	2.452	2.435	1.890	0.479

From the results in Table III-.1, the following observations have been made –

1) Layer type: All four thin films were determined to be $n-$type from the negative sign of V_H under any given case in the measurements. The negative carrier concentrations (n) in all four samples are way higher ($10^3 - 10^6\times$) than their respective intrinsic n, which implies that at such high n the effect of donor dopant ionisation can be negated by that of an acceptor dopant. Thus $n = |N_D - N_A|$, and this is known as dopant compensation.
2) Effect of T:
   a) With increasing T, ρ (or alternatively n) of GaAs layer increases, reaffirming the semiconducting nature of GaAs, wherein increasing dopant ionisation with temperature results in a linear increase in ρ and n. This is because
      i) $\left|\frac{d\mu_H(n)}{dT}\right| \gg \left|\frac{dn}{dT}\right|$
      ii) $\mu_H \approx \mu_{\text{impurity}} \propto n^{-1}$
      iii) $n \propto T, \because n = 2\left[\frac{2\pi m_n k_B T}{h^2}\right]^{3/2} \cdot e^{\frac{-(E_C - E_F)}{k_B T}}$
      iv) And, $\rho \propto (n \cdot \mu_H)^{-1}$.

      All of the above relations can be also be observed in the parameters of column 2 and 3 of Table III-.1.
   b) At a fixed temperature (295K) however, ρ of $GaAs_{0.75}P_{0.25}$ layer is lower than that of GaAs, simply because it has higher n w.r.t μ_H (as $\rho \propto (n \cdot \mu_H)^{-1}$).
3) μ_H dependence: At 295K, GaAs thin film has the highest μ_H because of its n being the lowest among other samples (least impurity scattering as seen in 2(a)ii). And at lower temperatures, n decreases further due to carrier freeze-out (as seen 2(a)iii).
4) Room temperature scattering times τ_{sc} $(= m_e^*\mu_H/e)$:
   a) For GaAs thin film ($m_e^* = 0.067m_e$)
      i) $\tau_{sc}@77K = \underline{1.18 \times 10^{-15}s}$
      ii) $\tau_{sc}@295K = \underline{4.94 \times 10^{-16}s}$
   b) Likewise, for $GaAs_{0.75}P_{0.25}$ thin film, τ_{sc} can be calculated, once its m_e^* is determined experimentally through cyclotron resonance.
5) Effect of substrate: Of all the layer parameters, only μ_H seems to be the most affected by the substrate type (columns 4 and 5 of Table III-.1) – direct E_g as in GaAs or indirect E_g as in GaP, which may affect the depletion width band curvature and hence μ_H.
6) Q: Of all the samples, the $GaAs_{0.75}P_{0.25}$ layer with GaP substrate had the lowest symmetry factor, implying that the point contacts were well placed as a square here.