

*Instruction Sheet*

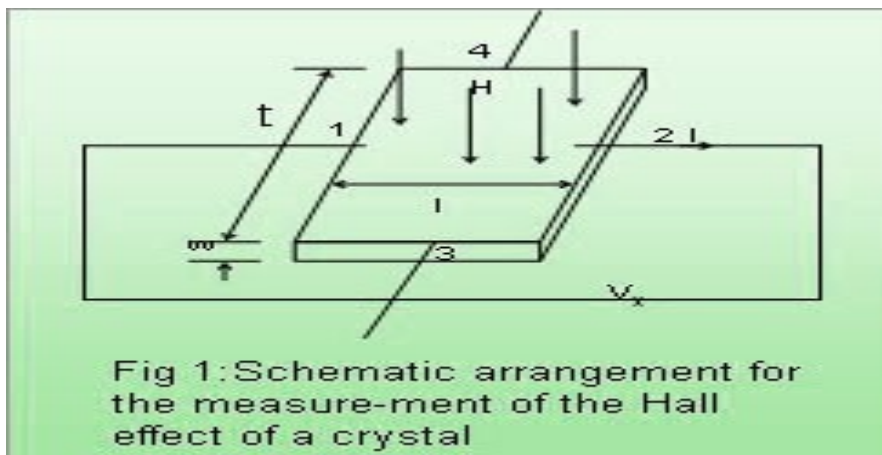
**DESIGN OF A THIN FILM HALL PROBE AND MEASUREMENTS**

**I. Objective**

Thin film based Hall effect measurement demands lot of research aspects related to its design. The aim of this experiment is to deposit a film (Bi, Sb) on an insulating substrate (glass), making layout of the probe, determine carrier density and mobility.

**II. Necessary theory**

When a current carrying conductor is placed in a transverse magnetic field, the Lorentz force on the moving charges produces a voltage perpendicular to both the field and the current. This is known as Hall effect. Measurements of the Hall voltage are used to determine the density and sign of the charge carriers in a conductor. When this is known, the effect can be used as a probe for magnetic field measurement.



The Hall coefficient can be theoretically determined from the formula

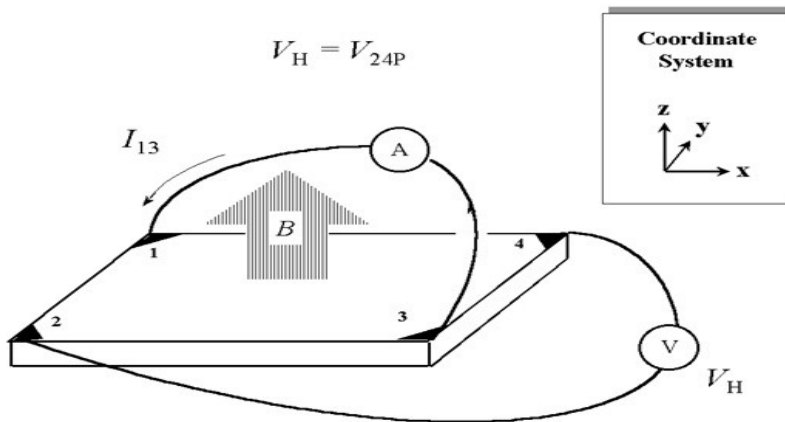
$$R_H = \frac{E_y}{J_x H} = \frac{E_y}{\sigma E_x H} = \frac{\mu_h^2 p - \mu_e^2 n}{e(\mu_h p + \mu_e n)^2} \dots\dots\dots (1)$$

[Ref: Detail formulation is given in the study material 1<sup>st</sup> Sem.]

The important point here is that the average diameters of the contacts, and sample thickness must be much smaller than the distance between the contacts.

The Hall measurement, carried out in the presence of a magnetic field, yields the sheet carrier density  $n_s$  and the bulk carrier density  $n$  or  $p$  (for  $n$ -type or  $p$ -type material) if the conducting layer thickness of the sample is known. **The severe problem comes from the large offset voltage caused by nonsymmetric contact placement, sample shape, and sometimes nonuniform temperature.**

The most common way to control this problem is to acquire two sets of Hall measurements, one for positive and one for negative magnetic field direction [Fig. 2]



**Fig. 2**

### III. Experimental steps

- i. Plan your own layout of the film (with connection)
- ii. Draw this layout in computer aided design software and take a print on a transparency sheet.
- iii. Cut the layout with utmost care from the transparency sheet, which is to be used as a mask during deposition
- iv. Load the material to be deposited on a filament/boat in the vacuum chamber.
- v. Obtain the lowest possible pressure using a rotary and diffusion pump combination (lower the pressure you achieve, better is the film quality)
- vi. Keep the mask in front of the substrate during deposition.
- vii. Vent the deposition chamber slowly and take out the film.
- viii. Make contacts with Ag paste (making good contact is the most important requirement)
- ix. Take the measurements (as per your knowledge in the I<sup>st</sup> sem. Lab and Appendix 1).

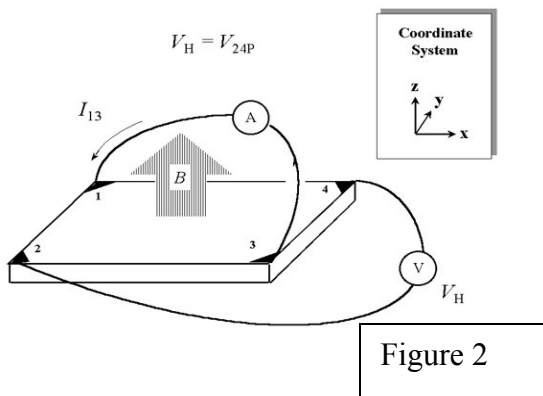
## IV. Task of this experiment

Calculate carrier density and Hall mobility for 150 nm and 400 nm and compare. Analyze the results and discuss independently.

### Appendix 1

#### van der Pauw method

Consider Fig. 2 again



Apply a positive magnetic field  $B$

Apply a current  $I_{13}$  to leads 1 and 3 and measure  $V_{24P}$

Apply a current  $I_{31}$  to leads 3 and 1 and measure  $V_{42P}$

Likewise, measure  $V_{13P}$  and  $V_{31P}$  with  $I_{42}$  and  $I_{24}$ , respectively

Reverse the magnetic field (negative  $B$ )

Likewise, measure  $V_{24N}$ ,  $V_{42N}$ ,  $V_{13N}$ , and  $V_{31N}$  with  $I_{13}$ ,  $I_{31}$ ,  $I_{42}$ , and  $I_{24}$ , respectively

The above eight measurements of Hall voltages  $V_{24P}$ ,  $V_{42P}$ ,  $V_{13P}$ ,  $V_{31P}$ ,  $V_{24N}$ ,  $V_{42N}$ ,  $V_{13N}$ , and  $V_{31N}$  determine the sample type ( $n$  or  $p$ ) and the sheet carrier density  $n_s$ . The Hall mobility can be determined from the sheet density  $n_s$  and the sheet resistance  $R_s$  obtained in the resistivity measurement (Appendix 2)

### Hall Calculations

Steps for the calculation of carrier density and Hall mobility are:

Calculate the following (be careful to maintain the signs of measured voltages to correct for the offset voltage):

$$V_C = V_{24P} - V_{24N}, V_D = V_{42P} - V_{42N},$$

$$V_E = V_{13P} - V_{13N}, \text{ and } V_F = V_{31P} - V_{31N}.$$

The sample type is determined from the polarity of the voltage sum  $V_C + V_D + V_E + V_F$ . If this sum is positive (negative), the sample is  $p$ -type ( $n$ -type).

The sheet carrier density (in units of  $\text{cm}^{-2}$ ) is calculated from

$$p_s = 8 \times 10^{-8} IB/[q(V_C + V_D + V_E + V_F)]$$

if the voltage sum is positive, or

$$n_s = |8 \times 10^{-8} IB/[q(V_C + V_D + V_E + V_F)]|$$

if the voltage sum is negative,

where  $B$  is the magnetic field in gauss (G) and  $I$  is the dc current in amperes (A).

The bulk carrier density (in units of  $\text{cm}^{-3}$ ) can be determined as follows if the conducting layer thickness  $d$  of the sample is known:

$$n = n_s/d$$

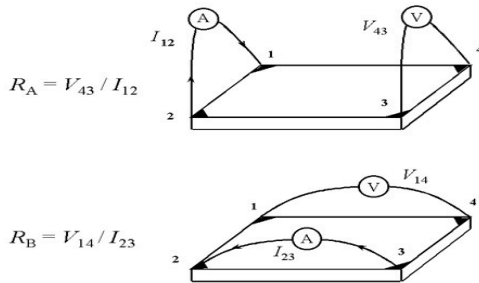
$$p = p_s/d$$

The Hall mobility  $\mu = 1/qn_s R_s$  (in units of  $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ ) is calculated from the sheet carrier density  $n_s$  (or  $p_s$ ) and the sheet resistance  $R_s$ ...

## Appendix 2:

### Thin film resistivity by van der Pauw method

Consider the following figure:



**Figure 1**

In order to determine the sheet resistance and the resistivity of the film follow the following steps:

Apply the current  $I_{21}$  and measure voltage  $V_{34}$

Reverse the polarity of the current ( $I_{12}$ ) and measure  $V_{43}$

Repeat for the remaining six values ( $V_{41}$ ,  $V_{14}$ ,  $V_{12}$ ,  $V_{21}$ ,  $V_{23}$ ,  $V_{32}$ )

Eight measurements of voltage yield the following eight values of resistance, all of which must be positive:

$$\begin{aligned} R_{21,34} &= V_{34}/I_{21}, R_{12,43} = V_{43}/I_{12}, \\ R_{32,41} &= V_{41}/I_{32}, R_{23,14} = V_{14}/I_{23}, \\ R_{43,12} &= V_{12}/I_{43}, R_{34,21} = V_{21}/I_{34}, \\ R_{14,23} &= V_{23}/I_{14}, R_{41,32} = V_{32}/I_{41}. \end{aligned} \quad (7)$$

Note that with this switching arrangement the voltmeter is reading only positive voltages, so the meter must be carefully zeroed.

Because the second half of this sequence of measurements is redundant, it permits important consistency checks on measurement repeatability, ohmic contact quality, and sample uniformity.

Measurement consistency following current reversal requires that:

$$\begin{aligned} R_{21,34} &= R_{12,43} & R_{43,12} &= R_{34,21} \\ R_{32,41} &= R_{23,14} & R_{14,23} &= R_{41,32} \end{aligned} \quad (8)$$

The reciprocity theorem requires that:

$$\begin{aligned} R_{21,34} + R_{12,43} &= R_{43,12} + R_{34,21}, \text{ and} \\ R_{32,41} + R_{23,14} &= R_{14,23} + R_{41,32}. \end{aligned} \quad (9)$$

If any of the above fail to be true within 5 % (preferably 3 %), investigate the [sources of error](#).

## Resistivity Calculations

The sheet resistance  $R_s$  can be determined from the two characteristic resistances

$$\begin{aligned} R_A &= (R_{21,34} + R_{12,43} + R_{43,12} + R_{34,21})/4 \text{ and} \\ R_B &= (R_{32,41} + R_{23,14} + R_{14,23} + R_{41,32})/4 \end{aligned} \quad (10)$$

via the van der Pauw equation

$$\exp(-R_A/R_s) + \exp(-R_B/R_s) = 1$$

[For numerical solution of the above equation see the routine below or use the software.

**If the conducting layer thickness  $d$  is known, the bulk resistivity  $\rho = R_s d$  can be calculated from  $R_s$ .**

Set the error limit  $\delta = 0.0005$ , corresponding to 0.05 %

Calculate the initial value of  $z_1$ , or  $z_0 = 2 \ln(2) / [\pi(R_A + R_B)]$

Calculate the  $i^{\text{th}}$  iteration of  $y_i = 1/\exp(\pi z_{i-1} R_A) + 1/\exp(\pi z_{i-1} R_B)$

Calculate the  $i^{\text{th}}$  iteration of  $z_i$  where

$$z_i = z_{i-1} - [(1-y_i)/\pi] / [R_A/\exp(\pi z_{i-1} R_A) + R_B/\exp(\pi z_{i-1} R_B)]$$

When  $(z_i - z_{i-1})/z_i$  is less than  $\delta$ , stop and calculate the sheet resistance  $R_s = 1/z_i$

The resistivity  $\rho$  is given by  $\rho = R_s d$ , where  $d$  is the thickness of the conducting layer