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New approach for measuring the microwave Hall mobility of semiconductors

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Measurement of Hall mobility in semiconductor samples using bimodal cavity method gives distinct advantages due to noncontact nature as well as the provision to measure anisotropic mobility. But the measurement approaches followed till now have a disadvantage of having high error values primarily due to the problem in evaluating the calibration constant of the whole experimental arrangement. This article brings out a new approach that removes such disadvantage and presents the calibration constant with 1% accuracy. The overall error in the carrier mobility values is within 5%. *© 2006 American Institute of Physics.* [DOI: 10.1063/1.2213167]

Investigations on the transport properties of elemental and compound semiconductors have been the subject of several workers over the last few decades. The importance of such studies has grown over the years because of their relevance not only to material characterization but also to the proper design of devices such as photovoltaic cells, photosensors, optocouplers, etc. One such important transport property is the mobility of carriers in the semiconductor. The measurement of mobility is generally performed using dc Hall effect, which requires the use of contacts on the sample. This makes the sample unusable, and therefore it is better to employ nondestructive techniques for this purpose.

It is well known that most of the measurements at microwave frequencies are generally noncontact and nondestructive in nature. Use of cavity perturbation technique for the study of photoconductivity is one such example. For nondestructive evaluation of the Hall mobility one can use the microwave Hall effect technique. This technique simultaneously provides the information regarding the conductivity and carrier concentration. Due to the noncontact nature, this technique is capable of measuring mobility of carriers even in powdered samples, thin films, biological materials, etc.

Microwave Hall effect was first observed by Cooke.[1] Rau and Caspari[2] observed the rotation of a plane polarized microwave signal as a transmitted wave through a germanium sample in a cylindrical waveguide. Watanabe[3,4] developed this technique to measure the electrical transport properties of low mobility samples and to verify high frequency effects on Hall mobility. This technique has been employed for measuring the mobility in the bulk semiconductors, organic semiconductors, powdered materials, and perovskites.[5–8] The introduction of network analyzers helped a lot in improving this technique further.[9] Chen *et al.*[10] studied the electrical transport properties of fine magnetic particles using this technique. Recently, Prati *et al.*[11] have applied this technique in calculating the mobility of the heterostructures.

To observe or measure the microwave Hall mobility, a circular or rectangular shaped bimodal cavity is used. The amount of power coupled between the two modes of the cavity due to external static magnetic field depends on the mobility of carriers as well as the external coupling factors. Though the methodology remains same, modifications are incorporated to ease the measurement procedure. For example, Al Zoubi *et al.*[12] used a double slug tuner to attain critical coupling at both the ports of the bimodal cavity. But the use of a double slug tuner makes the arrangement cumbersome, and therefore one finds it difficult to keep the cavity between the pole faces of the magnet. Moreover, application of the magnetic field affects the coupling, and therefore initial critical coupling condition often changes. This makes the whole arrangement erroneous. The work done by Schrape *et al.*[13] claimed that the rotation of a sample holder around the symmetry axis would yield cavity balancing, but it is not observed so.

It is well known that the amount of power coupled between the two modes of the cavity is very low. In order to enhance the sensitivity, a balanced bridge circuit called canceling channel is used. Though this improves the sensitivity, the amount of power coupled cannot be measured directly.

If there is a variation in the calibration constant due to change in the coupling constant of the cavity for each sample, then the measured mobility values will vary. Errors reported by earlier workers[11–14] were between 5% and 40%. Therefore, it is very important to have a proper measurement approach such that the calibration constant is independent of the sample used.

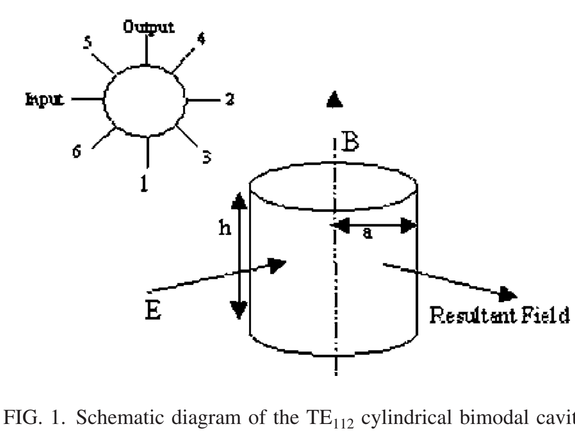

FIG. 1. Schematic diagram of the TE_{112} cylindrical bimodal cavity.

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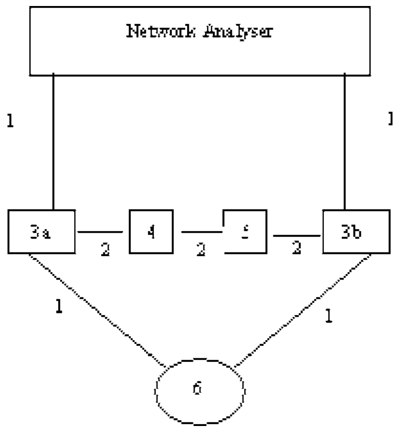

FIG. 2. Experimental arrangement of the microwave Hall effect technique.

TABLE I. The code, type and semiconductor material, resistivity, thickness and dc Hall mobility of the semiconductor samples used.

Sample code	Type and semiconductor material	Resistivity (Ω cm)	Thickness (μm)	dc Hall mobility values ($cm^2/V\,s$)
S1	*n*-type silicon	5000	470	1413
S2	*n*-type silicon	50	520	1404
S3	*n*-type silicon	4.0–7.0	356	1367
S4	*n*-type silicon	4.0–11.0	380	1372
S5	*n*-type silicon	1.0–10.0	590	1325
S6	*p*-type silicon	10	490	439
S7	*n*-type InSb	8900	480	8252

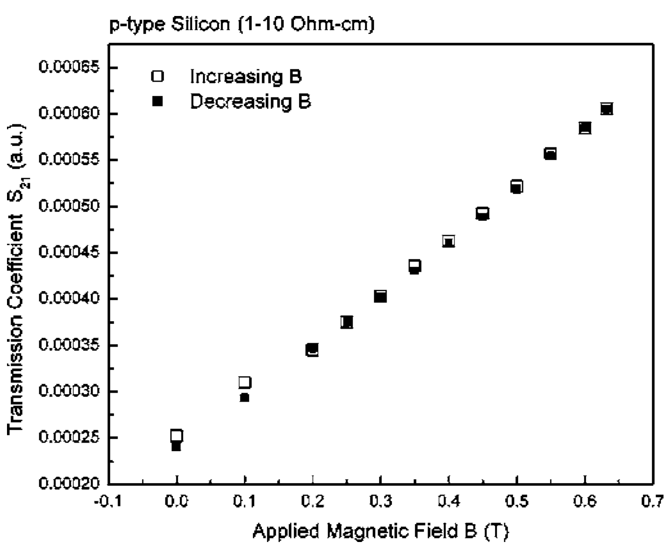

FIG. 3. Variation of the transmission coefficient with respect to the applied magnetic field for a *p*-type silicon semiconductor sample.

In this article, a new approach to evaluate the calibration constant of the measurement setup used for the microwave Hall mobility is proposed. The setup contains a bimodal cavity and a canceling channel. The calibration constant by this new approach is found to be constant for a given microwave cavity irrespective of sample dimension and property. This also decreases the error in measurement, and the errors obtained in the mobility values using the calibration constant are within 5%.

The basic bimodal cavity is a gold coated TE_{112} *X*-band cylindrical cavity. The radius and height of the cavity are 1.4 and 2.0 cm, respectively. Probe coupling is chosen for the excitation of the cavity. At two suitable positions of the cavity, coaxial probes were inserted for coupling. The coupling before and after insertion of the sample is found to be undercoupled. Necessary tuning probes were placed at 45° each to get mode degeneracy and orthogonality. The cavity resonated at 9.732 GHz, and unloaded quality factors at ports 1 and 2 were measured as 2577 and 3109, respectively. The reflection coefficients at ports 1 and 2 are 0.17 and 0.165, respectively. The typical circular bimodal cavity is shown in Fig. 1.

The block diagram of the microwave Hall effect arrangement is shown in Fig. 2. This consists of PNA Series 5230A Microwave Network Analyzer and a canceling channel. The canceling channel consists of Agilent 87300B (10 dB) coaxial directional couplers (3a and 3b), Agilent 8495B (0–70 dB), and 8495B (0–11 dB) coaxial step attenuators (4), and Spectrum Elecktrotechnik Gmbh LS-M018-2121 coaxial phase shifter (5). The canceling channel is necessary to remove the nonideal mode coupling.

Due to imperfections in the preparation of cavity, the primary and secondary modes of cavity do not resonate at the same frequency. So a tuning procedure was followed for attaining the mode degeneracy. Tuning was performed carefully by observing the parameters S_{11}, S_{22}, and S_{21}. Four capacitive tuning probes (indicated as 1, 2, 3, and 4 in Fig. 1), which are metallic in nature, are used to attain mode orthogonality and mode degeneracy. Two resistive tuning probes (indicated as 5 and 6 in Fig. 2) are graphite deposited. These probes are used to adjust the quality factors of both the modes.

A semiconductor sample is kept in a bimodal cavity at a position where the electric field is maximum and common to both the modes with the help of a specially fabricated Teflon sample holder. Since Teflon is a low lossy material, it only perturbs the resonant frequency. The excitation of one mode results in the electric field that oscillates the carriers at the microwave frequency in the sample. The application of the external static magnetic field (perpendicular to both the

TABLE II. The values of resonant frequency, standing wave ratio at ports 1 and 2, reflection coefficient at ports 1 and 2, and unloaded Q factor at ports 1 and 2 are given for samples S_1, S_2, and S_3.

Sample code	Resonant frequency (GHz)	Standing wave ratio at port 1 (ρ_{11})	Standing wave ratio at port 2 (ρ_{22})	Reflection coefficient at port 1 (Γ_{11})	Reflection coefficient at port 2 (Γ_{21})	Unloaded Q factor at port 1 (Q_{11})	Unloaded Q factor at port 2 (Q_{21})
S1	9.725	1.555	1.294	0.217	0.128	2212	2932
S2	9.722	1.582	1.383	0.225	0.161	2012	2431
S3	9.725	1.918	1.729	0.315	0.267	1558	1965

TABLE III. The transmission coefficient values for different canceling channel configurations for samples S_1, S_2, and S_3 at magnetic field of 0.6 T.

Sample code	Canceling channel configuration (a.u.)	Transmission coefficient	Calibration constant ($K\times 10^8$)
	1	3.1$E-3$	2.05
S1	2	1.79$E-3$	
	3	1.73$E-3$	
	1	7.24$E-3$	2.05
S2	2	3.52$E-3$	
	3	2.18$E-3$	
	1	1.10$E-2$	2.01
S3	2	9.01$E-3$	
	3	2.18$E-3$	

modes) results in the coupling of microwave power to the next mode due to the Hall effect. The change in transmitted power with the application of external static magnetic field is directly proportional to the mobility of carriers. The proportionality constant depends upon the sample property, value of the static magnetic field, and quality factor of the empty cavity. With incorporating the value of the static magnetic field and the actual change in the quality factor of the cavity due to the sample property, the proportionality constant can be used as the calibration constant (k_{NA}) to standardize the measurement procedure. With this calibration/proportionality constant, Trukhan[15,16] derived the following equation for the evaluation of the mobility for the critically coupled cavity at ports 1 and 2 having equal quality factors at both modes.

$$\mu = \frac{k_{\mathrm{NA}}\times 10^8}{B}\left(\frac{Q_0}{Q_0-Q_l}\right)S_{12}. \tag{1}$$

As it is not always possible to obtain critical coupling and equal quality factors for the orthogonal modes, it is better to use the basic equation for the nonequal input and output coupling.[17]

$$\mu = \frac{K}{B}\left[\left(1-\frac{Q_{11}}{Q_{10}}\right)\left(1-\frac{Q_{21}}{Q_{20}}\right)(1-\Gamma_{11})(1-\Gamma_{21})\right]^{-1/2}S_{12}, \tag{2}$$

where S_{12} is change in the transmission coefficient value; B is the dc magnetic field; Q_{10}, Q_{20}, Q_{11}, and Q_{21} are the unloaded and loaded quality factors at ports 1 and 2, respectively; Γ_{11} and Γ_{21} are loaded reflection coefficients of the input 1 and output 2, respectively.

Here the calibration constant K is of the order of 10^8. This constant takes care of the losses due to attenuation in the cables, components, interconnects, and imperfections in the cavity. It may be noted that the errors involved in the measurement procedures are of two kinds, viz., the intrinsic error based on the geometric factor of the cavity and the extrinsic error arising out of the use of the canceling channel. By using standard samples of known mobility values, one can obtain K with Eq. (2). The value of K is a constant for a given cavity. This is expected to reduce the error involved in the evaluation of mobility.

Table I gives the thickness, dc Hall mobility, and resistivity of the semiconductor samples (S1–S7) used in the measurement procedure.

Figure 3 shows the typical variation of a transmission coefficient (S_{21}) with respect to applied magnetic field (B) (increasing and decreasing) for a p-type silicon sample. From this graph, it is clear that with the application of magnetic field, the Hall power coupled is linear in nature and does not show any hysterisis.

In order to get more insight into the effect of cancellation channel configuration, three samples, S1, S2, and S3 with different resistivities, are used to obtain the variation of the transmission coefficient with respect to the applied magnetic field. The values of standing wave ratio, reflection coefficient, and unloaded quality factor at ports 1 and 2 and resonant frequency are given in Table II. The change in the transmitted power due to the application of the magnetic field for different combinations of canceling amplitude and phase is observed. Table III gives a typical variation of the transmission coefficient for a given magnetic field for three different canceling channel configurations. The value of K obtained using Eq. (2) is found to vary with the canceling channel configuration used (Table III). This indicates that the transmission coefficient obtained does not provide the true microwave Hall power generated by the magnetic field. To achieve the maximum change in the transmission coefficient, the best canceling channel configuration is chosen. The value of K obtained by this procedure is indicated in Table III in italics. It is to be noted that for the three samples chosen, the average value of K is within 1% of 2.03×10^8.

The above process is repeated for other semiconductor samples (S4–S7) to obtain the best canceling channel configuration. The evaluated microwave Hall mobilities for these samples using K obtained are presented in Table IV. It is now very clear that the error in the mobility values obtained by this approach is within 5%.

TABLE IV. Resonant frequency, standing wave ratio at ports 1 and 2, reflection coefficient at ports 1 and 2, unloaded quality factor at ports 1 and 2, transmission coefficient, and measured microwave Hall mobility are given for samples S4, S5, S6, and S7 [applied magnetic field (B)=0.6 T; calibration constant (K)=2.03×10^8].

Sample code	Resonant frequency (GHz)	Standing wave ratio at port 1 (ρ_{11})	Standing wave ratio at port 2 (ρ_{22})	Reflection coefficient at port 1 (Γ_{11})	Reflection coefficient at port 2 (Γ_{21})	Unloaded Q factor at port 1 (Q_{11})	Unloaded Q factor at port 2 (Q_{21})	Transmission coefficient (a.u.)	Microwave Hall mobility values ($\mathrm{cm^2/V\,s}$)
S4	9.724	2.257	1.951	0.386	0.322	1251	1413	1.44$E-2$	1428
S5	9.718	1.82	2.132	0.291	0.361	1690	1037	1.314$E-2$	1384
S6	9.718	1.738	2.127	0.269	0.36	1533	1344	4.04$E-3$	418
S7	9.721	1.478	1.294	0.193	0.128	2209	2854	2.237$E-2$	8359

A new approach in the measurement of the Hall mobility is proposed. It uses different canceling channel configurations. It is found that for a given applied static magnetic field, one can obtain the best canceling channel configuration that gives the maximum change in the transmission coefficient. This approach gives an accurate value in the calibration constant (within 1%). The measured microwave Hall mobility values for the different samples also fall within 5% of the dc Hall mobility values.

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