Determination of Hall Effect Parameters of Gallium Arsenide and Gallium Manganese Arsenide by Van Der Pauw Geometry

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Abstract

Gallium Arsenide (GaAs) has been used widely in electronic industry to make diodes and transistors. As a semiconductor, it can be doped up with impurities with magnetic properties such as manganese to increase its electron conductivity. The storage capacity of the electronic devices made of gallium manganese arsenide ($Ga_{1-x}Mn_xAs$) and the proportion of manganese atoms is worth studying. Here, GaAs was doped at different manganese levels, x, and the charge carrier concentrations at varied applied magnetic fields was investigated using Van der Pauw configuration. The tests were conducted at room temperature of 23^0C with magnetic field, $0.9 \leq B \leq 3.6$mT and direct current of 1.19A. All the samples were studied for their hall voltage V_H, carrier mobility μ, hall resistivity ρ_H and charge carrier concentration for different values of x. It was determined for $Ga_{1-x}Mn_xAs$, $10\% \leq x \leq 20\%$ range, has maximum hall resistivity at $B \approx 1.9$ mT. For x=10%, $\rho_H \approx 44.0\Omega.m$; x=20%, $\rho_H \approx 79.0\Omega.m$ and for x=1%, the applied magnetic field has no effect on hall resistivity at initial states until $B \approx 1.7$mT. Beyond this point, magnetic field increases linearly with the hall resistivity to a maximum of $\rho_H \approx 72.0\Omega.m$. Maximum hall resistivity for x=50% was $\rho_H \approx 2596.0\Omega.m$ at $B \approx 0.9mT$. For $0 \leq x \leq 20\%$, carrier mobility μ, was of order of $10^{-7}\,m^2V^{-1}s^{-1}$ while for $x = 50\%$, μ was of order $10^{-9}\,m^2V^{-1}s^{-1}$. It was found out that the most probable doping percentage of GaAs with Mn dopants is approximately 20% and 10% as they show a hysteric response to an applied magnetic field. It suggests a good doping level of GaAs for making of volatile memory chips.

Keywords: Van der pauw geometry, hall resistivity, gallium arsenide, gallium manganese arsenide, heat dissipation, doping, electron conductivity

1. Introduction

Semiconductors are materials whose energy gap lies precisely between that of insulators and metals. The electrical characteristics of semiconductors can be altered easily by addition of tiny impurities from their initial intrinsic state. The impurity atoms added into the crystal lattice act as sources of free charge carriers (Sawicki, 2004; Sadowski *et al.*, 2006). Desired electrical properties of semiconductors can be engineered by controlling the type of the impurity and its concentration. The determining factor for conduction in semiconductors is the nature of energy gap between the valence band and the conduction band. The valence bands are filled completely and cannot conduct significant current as the electrons are located on the orbitals by Pauli Exclusion Principle.

1.1 Charge carrier conduction (electrons and holes)

GaAs is a compound intrinsic semiconductor that can be doped with manganese atoms to generate free conduction charge carriers. GaAs has paired electrons and all its orbitals are completely filled and thus do not have intrinsic magnetic moment. Upon incorporation of Mn atoms, the Mn ions replaces Ga ions in the GaAs crystal lattice sites and they act as single electron acceptors (Sadowski *et al*., 2002) each contribute one hole as a free charge carrier to the lattice for conduction of electric current. If manganese ions in the formed (Ga,Mn)As are in substitution positions, the carrier concentration is equivalent to the manganese concentrations of approximate order of $10^{25}m^{-3}$ (Johnson *et al*., 2010). The (Ga,Mn)As thus shows ferromagnetism due to the half filled d shells of manganese atoms. The heat dissipation in relation to the hall resistance, memory effect and applied magnetic field of Mn-doped GaAs at different doping levels ought to be studied. The study is anticipated to provide the basis for the fabrication of miniature electronic devices. It will see the advancement in nano-technology and high speed processing electronic machines. There are several designs for Hall Effect study approach: rectangular, cyclic, square and Van der pauw. Since the films under investigation are thin (in nano scale), it can be studied using Van der pauw technique as it provides the most average hall measurements than the other forms (Poggio *et al*., 2005; Matsumura and Sato, 2010).

2. Materials and method

Teslameter in mT scale, coils (600 turns), digital multmeter, digital nanoammeter and power supply with ranges of 0≤I≤5A, 0≤V≤18V (DC) and 0≤I≤5A, 2≤V≤15V (AC) were used in the Van der Pauw geometry (Matsumura and Sato, 2010). Applied magnetic field of 0.9 mT was used together with a direct current of 1.19A passed through the middle of opposite ends of each sample. The carrier density and hall mobility were calculated from the data obtained from the set up represented in Fig. 1 using the following relations for V_C ,V_D ,V_E and V_F i.e., $V_C = V_{24P} - V_{24n}$,$V_D = V_{42P} - V_{42n}$, $V_E = V_{13P} - V_{13n}$ and $V_F = V_{31P} - V_{31n}$ where p and n refers to the positive and negative magnetic field recorded values of voltages respectively. The hall voltage was obtained from the algebraic sum of the measured voltages. The determined hall voltage was then used for the determination of the sheet carrier density P_S, and consequently, bulk carrier density *P*, and hall mobility from eqns (1.0) respectively.

$$p_S = \frac{IB}{e|V_H|}, p = \frac{p_S}{d}, \ \mu = \frac{1}{qp_S R_S} \tag{1.0}$$

Hall resistivities were determined from Fig. 2 (a) and (b) using the following procedure: The current I_{21} was applied and voltage V_{34} measured. The current was then reversed i.e., I_{12} and V_{43} was measured. Similar steps were followed to measure $V_{41}, V_{14}, V_{12}, V_{21}, V_{23}$ and V_{32}. Ohm's law and the data obtained were then used to determine hall resistances for each corresponding sets of voltages and currents e.g., $R_{21,34} = {V_{34}}/{I_{21}}$. Eqn (1.1) was used to determine the sheet resistances, R_S with characteristic resistances (R_A and R_B) that were obtained from eqns (1.2).

$$\exp\left(-\pi R_A / R_S\right) + \exp\left(-\pi R_B / R_S\right) = 1 \tag{1.1}$$

$$R_A = \frac{\left(R_{21,34} + R_{12,43} + R_{43,12} + R_{34,21}\right)}{4}, \ R_B = \frac{\left(R_{32,41} + R_{23,14} + R_{14,23} + R_{41,32}\right)}{4} \tag{1.2}$$

Hence, hall resistivity was determined from $\rho = R_S d$ where *d* was 500nm.

3. Results and discussions

When the amount of Mn^{2+} is increased from 0 to 20%, hall resistivity reduces from 78.14Ω.m to 2.37Ω.m respectively. At Mn^{2+} proportion of 50%, hall resistivity increases drastically to approximately 2569Ω.m. This is the case when applied magnetic field of B=0.9mT is applied. The drastic rise in hall resistivity at x=50% shows that the semiconductor properties of the (Ga,Mn)As DMS change to almost metallic. This is the approximate doping level beyond which the DMS loses its semiconducting properties. Otherwise, the peculiar property observed is not exactly metallic but seems to be. Below x=50%, manganese dopants make GaAs to increase its electrical conductivity. This is evidenced by the reduction of hall resistivity from 78.14Ω.m for pure GaAs to 2.37Ω.m for x=20% as shown in Table 1. An increase in magnetic field from 0.9mT to 1.8mT can alter the electronic transport of GaAs. At this point (1.8mT), the magnetic field is sufficient to perturb the GaAs lattice structure that results into splitting (Zeeman Effect) and the charge carriers are set free to move (Matsukura *et al*., 2002). This is evidenced by a reduced hall resistivity of 42.16Ω.m from 78.14Ω.m suggesting an increase in electron conductivity. Otherwise for x=1%, x=10% and x=20%, Zeeman Effect doesn't play significant role. This implies that the electronic conductivity dependence of GaAs on the concentration of Mn^{2+} is inhibited by the magnetic energy provided by B=1.8mT; as it is not enough to support GaAs atomic splitting. At degenerate doping (x=50%), magnetic field of B=1.8mT produces magnetic energy enough to set the charge carriers free hence, enhances carrier transport. This can be seen from the reduction of hall resistivity as magnetic field is increased to 1.8mT for x=50%. As magnetic field is increased further to B=3.6mT, GaAs (x=0) generates more free charge carriers. This eventually increases the charge carrier conductivity and transport as shown by a further reduction in hall resistivity. At this point, perturbation of the crystal structure is increased by a further rise in magnetic energy. When GaAs is doped with 1% Manganese impurity atoms and magnetic field strength increased to 3.6mT, there is a steady increase in hall resistivity. This corresponds to a drop in the conductivity of the resultant Dilute Magnetic Semiconductor (DMS). Therefore, it suggests that the charge carrier concentration has been reduced or the amount of charge carriers set free decline as magnetic field is increased. The incorporation of Mn atoms alters the GaAs lattice structure and since the % of Mn atoms is low (1%), an increased magnetic field doesn't generate more charge carriers but localises them: As Mn_{Ga} acceptors become single donors rather than double donors.

In Fig. 3, it can be observed that the hall resistivity increased steadily with an increase in applied magnetic field. The maximum peak is at B~1.90mT. It is also observed that beyond this peak value, the hall resistivity decreases. The maximum hall resistivity at the peak point is $\rho_H \approx 79.0\Omega.m$. At the maximum peak there is a change of state. The GaMnAs become more of a metal than a semiconductor. The increase in B field beyond B~1.85mT produces an extra magnetic energy sufficient to engage more free charge carriers in electron conduction. Their concentration increases from that of 1% and hall resistivity decreases from that at 1%. At this region, the conductivity rapidly increases. The increased free charge carriers are attributed to the perturbation of the crystal by the B field energy. Otherwise at B>~2.7mT, the drop in hall resistivity is low. Here the conductivity increases slowly. This implies that the charge carriers become localised on the valence band and they are few in the conduction band. This is due to a further splitting of the bands that increases the band gap further and most of the conduction charge carriers reaching to the conduction band reduces. At B<~1.85mT, the hall resistivity is seen to increase uniformly from zero to approximately 79.0Ω.m. This increase suggests a decrease in conductivity and it shows that the charge carriers available for conduction of hall current reduce as B field increases. At this region, the Mn_{Ga} acceptors are delocalised and the pertubation from the increasing B field is insufficient to dislodge more charge carriers from their lattice positions. The Mn atoms at 20%

attach themselves intact on the Ga sites whose proportion reduces to 80%. So, generally Mn acceptor dopants % of 20, has maximum hall resistivity of approximately 79.0Ω.m and the hall resistance is also maximum at a similar point (B~1.85mT). At this point, the heat dissipated through joule heating is maximum and much less than that for X=50%.

In Table 2, $Ga_{0.8}Mn_{0.2}As$ is tested to be a p type extrinsic semiconductor shown by a positive hall voltage. The hall mobility also appears to have increased drastically to $5.29x10^{-7}m^2v^{-1}s^{-1}$ that suggests abundant free conduction charge carriers which is due to high doping level as compared to others at x=10%. In Fig. 4, the peak point is almost similar to the case in Fig. 3 i.e., B≈1.9mT but the hall resistivity peak value is approximately 44.0 Ω.m which is a reduction from 79.0 Ω.m for $Ga_{0.8}Mn_{0.2}As$. Significantly, the behaviours of the variations of hall resistivity with applied magnetic field are similar for x=10% and x=20%. As applied B field is increased, the state of disorder in the crystal lattice of $Ga_{0.9}Mn_{0.1}As$ increases due to the perceived perturbation caused by an increasing magnetic energy. The hall resistance increases while the carrier conductivity decreases until the maximum peak is reached i.e., the saturation point−the point at which the hall resistance is constant with respect to an increasing applied magnetic field. Beyond, the saturation point, the charge carriers become freer and many therefore, the carrier current density increases as well as conductivity. This region shows electrical properties similar to that of a metal though at a lower level. Further, the variation of hall resistivity over the peak point falls down in curvilinear manner to approximately its initial hall resistivity state showing a hysteric behaviour.

In Fig. 5, there is no saturation point and the behaviour of the curve for $0.9mT \leq B \leq 3.6mT$ is not similar to those of x=10% and x=20%. Here, the hall resistivity varies almost linearly with the applied magnetic field. At initial state, $0.9<B<1.8mT$, the hall resistivity is constant but beyond this point it increases to the maximum magnetic field. The increase suggests the reducing conductivity. Here, there is no hysteric behaviour and does not show a memory effect. This shows that the charge carriers present in the $Ga_{99.99}Mn_{0.01}As$ seem to be few and has a lower conductivity. The state of disorder due to 1% Mn incorporation and applied magnetic field energy is minimal. It is not sufficient to generate more free charge carriers. GaAs being an intrinsic compound semiconductor shows odd properties from those disordered by imperfections of Mn atoms as in Fig. 6. It shows metallic properties as applied magnetic field increases from 0.9mT to 1.9mT. This variation is linear and it shows that the hall conductivity is in an increasing trend which further suggests an increasing free charge carriers. The hall current increases drastically as magnetic field energy increases. This observation is attributed to the splitting of the energy bands by magnetic energy that perturbs the crystal lattice to release the negative charge carriers that shift to the conduction band as in Table 2. The transition energy is facilitated by the increased applied magnetic field. This shows the effect of Mn atoms on the conductivity of GaAs. In comparison to the doped cases, Mn atoms tend to suppress or localise the charge carriers into the valence band of GaMnAs lattice structure at low magnetic fields. Thus, the imperfections caused by Mn are defective to the conductivity of GaAs at lower fields but at higher B-fields, the energy from the applied fields generates the conduction charge carriers (majority and minority). The incorporation of Mn^{2+} atoms renders GaAs an insulator at low B fields and can become good conductors at higher B fields. The maximum hall resistivity is approximately 78.0Ω.m and its minimum is approximately 42.0Ω.m. Here, it is observed two phases that repeat themselves after some interval of magnetic field: metallic, semiconducting then metallic. In considering, the saturation points, it is seen that for GaAs the minimum saturation point coincides approximately with the maximum saturation points for the GaAs Mn-doped cases.

At B>1.9mT, the GaAs turns out to be semiconducting as the hall conductivity reduces with increasing B field up to another maximum saturation point at B≈2.7mT beyond which the charge carriers become freer and many once again. During, semiconducting phase, the charge carriers are frozen into their localised states. This phenomenon assumes a step-like structure or quantization of states. $Ga_{0.5}Mn_{0.5}As$ is the highly doped GaAs of the films under study. At this doping level the process can be described as degenerate. This implies that the resultant extrinsic semiconductor behave as a metal as a whole at all times irrespective of the applied magnetic field energy. The charge carriers are superfluous and very free to move in the conduction band. The band gap is perceived to have been reduced a great deal (overlap) that the charge carriers can easily jump from the valence band to the conduction band even with little applied magnetic field.

In reference to Fig. 7, the hall resistivity is generally very high thus hall conductivity is very low. This is in analogy with the case of a metal whose conductivity behaviour is explained by Drude theory for conduction charge carriers considered as a sea. In metals, any induction of external energy sets the (charge carriers) free electrons to vibrate vigorously and the rate of collisions increases. This makes the resistance of a metal higher and its conductivity lower. Otherwise, the conductivity appears to be affected by applied magnetic field but within the metallic region. The maximum hall resistivity is recorded to be approximately 2596 Ω.m at B≈0.9mT. This is the point of minimum hall conductivity for 50% Mn-doped GaAs at B≈0.9mT. It has the least hall resistivity of approximately 1350Ω.m at B≈2.0mT which has the highest conductivity.

Beyond B≈2.0mT, the conductivity decreases linearly and gently with the applied magnetic field. The behavior assumes a hollow curvature at an equillibrium position of approximately 1350 Ω.m and approximately 2.0mT and does not show a hysteric response to the magnetic field. So, B-field of about 2.2mT produces energy enough to freeze the charge carriers into their localised positions in the lattice crystal and it becomes difficult for them to be free to conduct. In reference to Table 2, it can be observed that $Ga_{0.5}Mn_{0.5}As$ has the lowest hall mobility of the order of 10^{-9}. This suggests that there are many charge carriers which when magnetic field is applied sets them into rigorous collision and scatter greatly a phenomenon of alloy scattering. The rampant scattering increases the hall resistivity and thus lowers the hall conductivity. Generally, the hall currents during the study was measured to be in the order of 10^{-9}A (nA scale) whose value was observed to be highest for 50% Mn-doped GaAs. The hall voltages were obtained in the order of 10^{-3}V (mV scale) except for the degenerately doped GaAs which recorded hall voltage in the zeroth order (10^{0}V).

In refernce to Fig. 8, the hall mobility is observed to increase almost linearly with the increase in the manganese impurity atoms upto 20% of $\mu=5.2\text{x}10^{-7}m^2V^{-1}S^{-1}$. This shows that the electron transport speed increases. Thus, if diodes and transitors can be fabricated using compound semiconductor, GaAs doped with Mn at 20%, it can produce electronic devices that can process data at a very high speed. Otherwise, beyond 20% doping level the hall mobility is seen to decline drastically. At 50% doping level, hall mobility is approximately $4.5\text{x}10^{-9}m^2V^{-1}S^{-1}$ which is a very small value compared with the others less than 20%. This means that the doping levels beyond 20% are not suitable in electronic fabrication as it suggests devices operating at low speed.

4. Conclusions

From the findings of the collected data and their analysis in reference to the specific objective of study, the probable Mn doping levels on GaAs has been explained. This is in regard to the determined maximum or average hall resistivity and hall mobility of the GaAs doped with Mn atoms at varied percentages. Usually, high resistive materials experience the highest joule heating as they conduct electric current and the heat dissipated becomes a defect on the efficiency and lifetimes of most electronic devices. In compound semiconductors such as GaAs doped with manganese impurities at approximately 50% are not suitable for use in making electronic devices. As observed from the obtained results, GaAs doped with Mn of approximately 50% recorded an enormous hall resistivity without hysteric response to the applied magnetic field. This corresponds to a very high hall resistance which impedes the hall current thus dissipating a very large amount of heat. Also, on the basis of its low hall mobility, it shows that it has many free conduction charge carriers that collide frequently and thus not efficient to pass information (data) effectively within a short period of time. Thus, GaAs doped with Mn at 50% is not suitable for use in fabrication of transistors and diodes since they don't have memory response that can store and process data at high speed. Otherwise, doping at x=20% is the most appropriate in terms of data transport, heat dissipation and memory effect. Here, there is large hall mobility suggesting that the charge carrier carrying data (information) can be transported quickly. Thus, the higher mobility Mn-doped GaAs is the best film to be used in the diodes, transistors and ICs fabrication. Heat dissipated is less than for the case of degenerate doping shown by low average hall resistivity of approximately 78.0 Ω.m. In comparison to the 10% Mn doping levels, the hall resistivity and hysteric responses are similar but the difference is in the hall mobility. This Hall Effect parameter suggests 20% doping level is the most suitable to adopt as it has a larger hall mobility than the one of 10%. The electronic devices made of GaAs doped with Mn of ~20% have longer life times. Indeed, it provides a basis for the fabrication of even smaller sized electronic devices since the danger of heat damage will have been factored in during growth and during its doping with manganese atoms.

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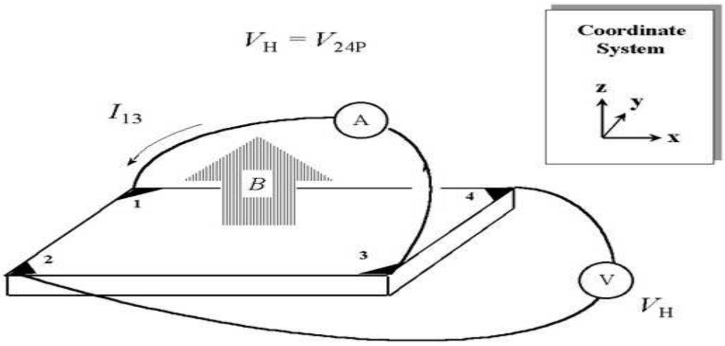

Fig. 1: Van der pauw geometry for Hall voltage measurements

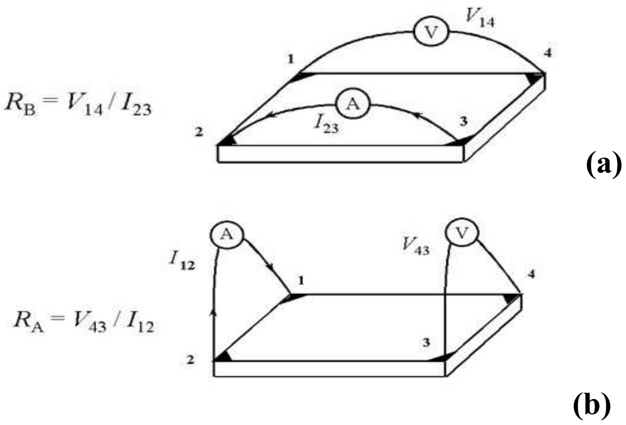

Fig. 2: (**a**) and (**b**) Van der pauw experimental circuit diagrams for measuring R_A and R_B

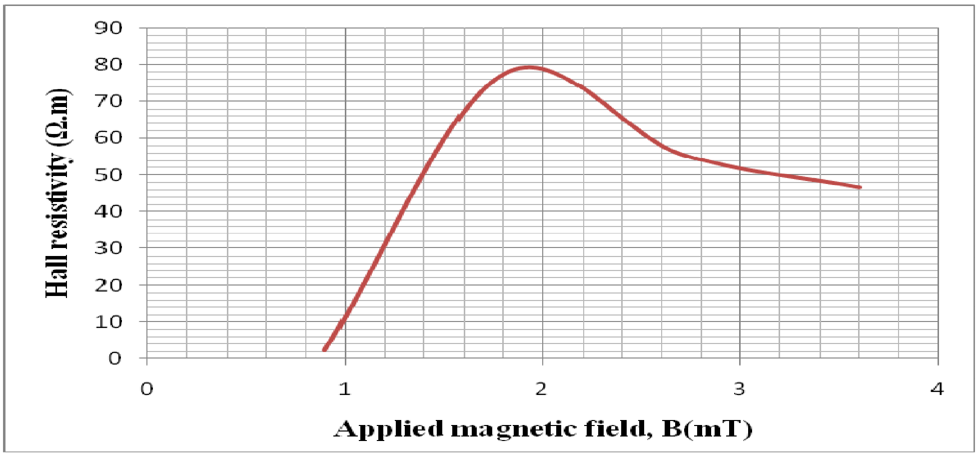

Fig. 3: Hall resistivity versus magnetic field of $Ga_{1-x}Mn_xAs$, x=20%

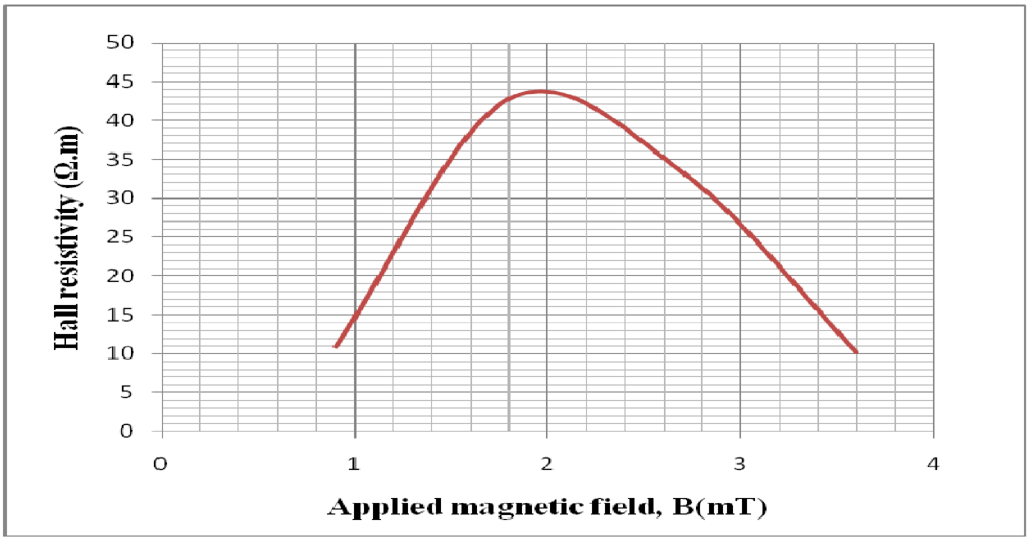

Fig 4: Applied magnetic field versus hall resisitivity of $Ga_{1-x}Mn_xAs$; x=10%

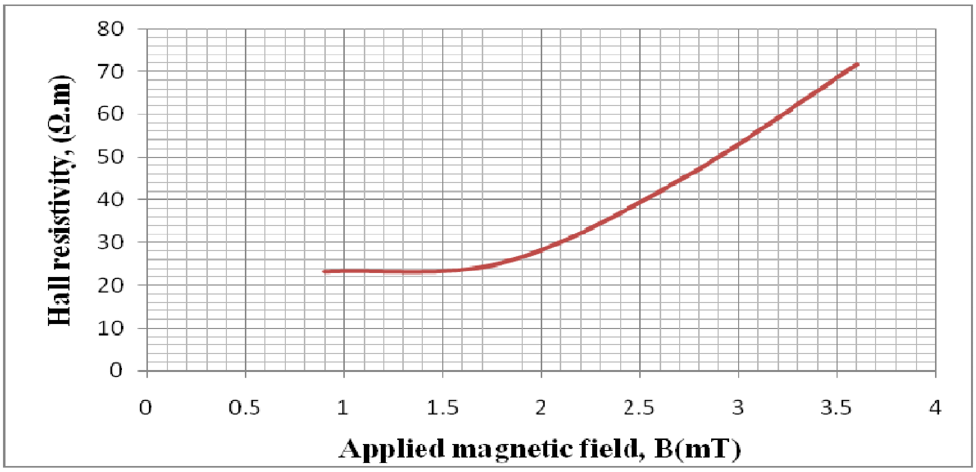

Fig 5: Applied magnetic field versus hall resisitivity of $Ga_{1-x}Mn_xAs$; x=1%

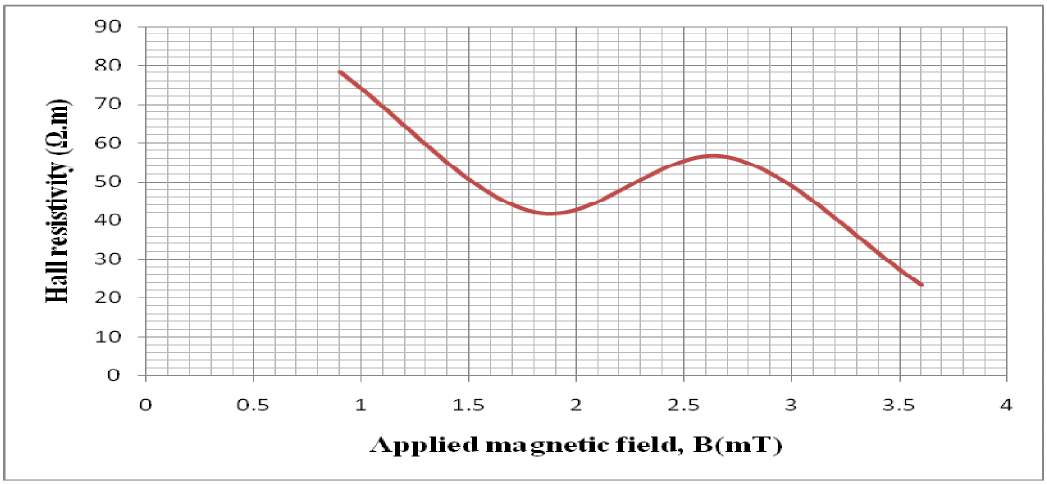

Fig. 6: Hall resistivity versus magnetic field of GaAs

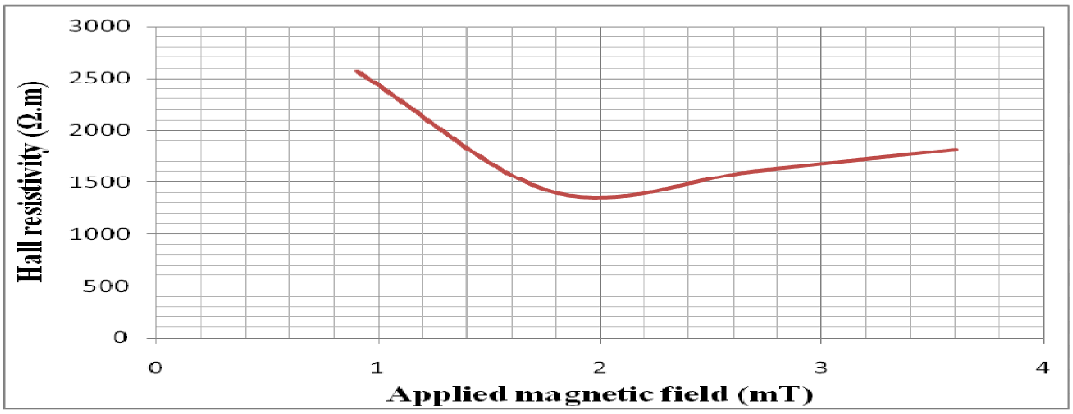

Fig. 7: Hall resistivity versus applied magnetic field of $Ga_{1-x}Mn_xAs$; x=50%

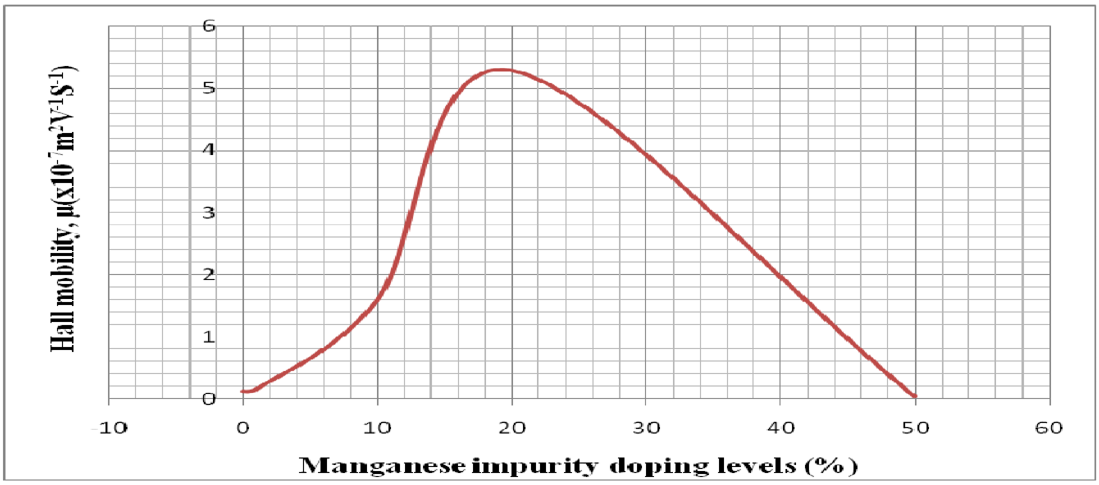

Fig. 8: Variation of hall mobility with the impurity doping levels of Manganese in GaAs

Table 1: Applied magnetic fields and hall resistivity of $Ga_{1-x}Mn_xAs$

	X=10%	X=20%	X=1%	X=0	X=50%
B(mT)	ρ_H (Ω.m)	ρ_H (Ω.m)	ρ_H (Ω.m)	ρ_H (Ω.m)	ρ_H (Ω.m)
0.9	10.89	2.37	23.31	78.14	2569.36
1.8	42.78	77.43	25.34	42.16	1397.89
2.7	33.27	55.70	44.59	56.28	1608.17
3.6	10.16	46.74	71.63	23.36	1817.35

Table 2: Charge carrier concentration, hall mobility and hall voltage of $Ga_{1-x}Mn_xAs$ for applied current of 1.19A and applied magnetic field of 0.9mT

$Ga_{1-x}Mn_xAs$	Carrier concentration ($x10^{25}m^{-3}$)	Hall mobility ($m^2v^{-1}s^{-1}$)	V_H (mV)
X=0	0.638	$0.13x10^{-7}$	-2.10
X=1%	1.673	$0.16x10^{-7}$	0.80
X=10%	0.361	$1.59x10^{-7}$	3.71
X=20%	0.498	$5.29x10^{-7}$	2.70
X=50%	0.05	$4.5x10^{-9}$	0.025

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