

# Phonon interaction and variation of deformation potential with temperature and concentration in diluted $\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$ quantum well

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The carrier transport properties for two dimensional diluted  $\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$  have been calculated via electron acoustical phonon interaction on the basis of deformation potential coupling mechanism for the different concentrations of Mn ( $x \leq 10\%$ ) at different temperatures. The acoustic phonon scattering rate increases with the energy and decreases with the manganese concentration. The contribution of acoustic phonons in the variation of resistivity for different manganese concentrations and threshold thermal energy have also been determined. The temperature and concentration both affect the acoustic phonon scattering rate. Therefore, the resistivity varies due to the effect of these on the acoustical deformation potential (ADP).

**Keywords:** Phonons interaction, Diluted magnetic semiconductor

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## 1 Introduction

In recent years, manganese doped III-V ferromagnetic semiconductors like  $\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$  and  $\text{Ga}_{(1-x)}\text{Mn}_x\text{As}$  known as diluted magnetic semiconductors (DMS) have attracted great attention as a potential application for spintronics due to their successful demonstration of spin injection into the semiconductor devices. By using semiconductor  $\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$  ( $x \leq 0.1$ ) of high crystal quality, with its  $T_c$  beyond room temperature, some magnetic, electronic and photonic devices including spin transistors operating at very low power, mobile applications, optical emitters with encoded emitters with encoded information through their polarized light output, and Magnetic Random Access Memory<sup>1,2</sup> (MRAM) will be convenient to make. The transport properties of bulk materials and two dimensional structures are of great importance in materials' assessment particularly in developing and optimizing new device structures and highly affected by the phonon scattering, which is inherent to the solid state of matter. The electron mobility is influenced strongly by the interaction of electrons with phonons. The saturation velocity of carriers in a semiconductor provides the speed of a microelectronic device fabricated from this semiconductor<sup>3</sup>. Evidently, the practical switching time of such a microelectronic device will be limited

by the saturation velocity and clearly therefore, the phonons play major role in the fundamental practical applications and limits of such microelectronic devices. The dynamics of carrier capture in the active quantum well region of a polar semiconductor quantum well laser also introduces the importance of carrier-phonon interactions in modern semiconductor devices. It is observed that the loss of energy by an electron depends on the rates for both phonon absorption and phonon emission. Further, it is observed that the dimensional confinement of phonons in inter-sub-band semiconductor lasers changes the laser gain and leads to enhanced population inversion in some asymmetric double barrier quantum well lasers<sup>4</sup>. The dimensional confinement of phonons restricts the phase space of phonon wavevector and hence, the carrier phonon interactions in nanostructures are modified by the phonon confinement. In the present work, the electron-acoustic phonon scattering rate in two-dimensional  $\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$  alloy by using the deformation potential coupling mechanism has been calculated. The deformation potential coupling between electrons and phonons has been utilized quite successfully previously in the case of bulk as well as semiconductor nanostructure to calculate acoustic-phonon scattering rate<sup>4,5</sup>.

## 2 Theory

As carriers traverse a device, their motion is frequently interrupted by collisions with phonons (acoustical and optical), impurity atoms, crystal defects, etc<sup>6</sup>. The transition rate which is the probability per unit time that a carrier with crystal momentum  $p$  scatters to a state with a crystal momentum  $p'$ , is calculated by using the Fermi's golden rule by considering acoustical phonons potential as perturbing potential and can be given as:

$$S(p, p') = \frac{2\pi}{\eta} \left| H_{p'p} \right|^2 \delta(E(p') - E(p) - \Delta E) \quad \dots (1)$$

where,  $H_{p'p}$  is the matrix element of scattering potential.  $\Delta E$  is the change in energy caused by scattering event. Usually, the interaction with acoustic phonons in semiconductors is expressed in terms of the so-called deformation potential<sup>7</sup>. The matrix element  $H_{pp'}$  is given by:

$$H_{pp'} = \frac{1}{\Omega} \int e^{-ip'r/\hbar} U_S(r) e^{ip'r/\hbar} d^3r \quad \dots (2)$$

where,  $U_S(r)$  is the perturbing potential due to acoustical phonons and given by:

$$U_S = \mathbf{K}_\beta u_\beta = K_\beta A_\beta e^{i(\beta z - \omega t)} + \mathbf{K}_\beta A_\beta^* e^{-i(\beta z - \omega t)} \quad \dots (3)$$

Where,  $A_\beta$  is the amplitude of the carrier plane wave and  $\mathbf{K}_\beta$  is the wavevector.

The scattering rate can be obtained by summing over all final states as:

$$\frac{1}{\tau(p)} = \sum_{p', \uparrow} S(p, p') \quad \dots (4)$$

Converting the sum to an integral and solving Eq. (4), we get:

$$\frac{1}{2} = \left( \frac{\Omega}{4\pi^2} \right) \int_{\beta_{\min}}^{\beta_{\max}} \left( N_\beta + \frac{1}{2} \mu \frac{1}{2} \right) C_\beta \beta^2 d\beta \quad \dots (5)$$

where  $\beta_{\min}$  and  $\beta_{\max}$  are the minimum and maximum values of  $\beta$  for which the agreement of the  $\delta$ -function in the solution of Eq. (4) goes to zero. The  $\beta_{\min}$  and  $\beta_{\max}$  are the minimum and maximum phonon vectors

for which both energy and momentum are conserved.  $C_\beta$  defines the deformation potential scattering for acoustic phonons and given as:

$$C_\beta = \frac{\pi m^* D_A^2}{\eta \rho v_s p \Omega} \quad \dots (6)$$

To evaluate scattering rates for acoustic phonon scattering via the deformation potential scattering in 2D nanostructure, Eq. (5) can be solved by substituting the value of  $C_\beta$  from Eq. (6) for the acoustical deformation potential scattering (ADP scattering)

$$\frac{1}{\tau} = \frac{\pi D_A^2 k_B T_L}{W \eta C_l} g_c(E) \quad \dots (7)$$

where,  $g_c(E)$  is the density of states in 2D confined system.  $W$  is a width of the quantum well.  $D_A$  is the acoustic deformation potential (ADP) given by

$$D_A = \mathbf{K}_\beta T_L (M/m^*)^{1/2}, \text{ where } m^* = \frac{\eta^2}{\partial^2 E / \partial k^2}$$

is electron effective mass and  $M$  is atomic mass (in g), which varies with lattice temperature<sup>7</sup> and  $C_l$  is the longitudinal elastic constant.

The carrier acoustic phonon contribution to the resistivity can be calculated by:

$$\rho = \frac{m^*}{ne^2 \tau} \quad \dots (8)$$

where  $e$  is electronic charge,  $n$  the number of charge carriers and  $\tau$  is the carrier acoustic phonon relaxation time. The input parameters for the calculation of scattering rate and resistivity are the deformation potential and effective mass calculated from the expression given in Eq. (8) and are presented in Table 1.

## 3 Results and Discussion

The electron acoustic phonon scattering rates calculated by using Eq. (7) for the two-dimensional  $\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$  alloy (for  $0.0 < x < 0.1$ ) have been presented in Figure 1. The scattering rate for all considered concentration of Mn increases with the energy and it is almost the same for all considered

concentrations for lower energy but varies exponentially for higher energy, which can be seen from the inset of Fig. 1. This is due to the fact that the deformation potential scattering increases due to the enhancement of phonon density of states resulting from confinement of phonons. We also present the variation of scattering rate with respect to the Mn concentration in Figure 2, to understand the effect of Mn doping on scattering rate and observe that the scattering rate decreases with increase in Mn concentration due to the increase in the effective mass and total atomic mass simultaneously, but the effect of atomic mass is more significant than the effective mass on ADP. Fig. 3 shows the behaviour of acoustic deformation potential (ADP) for different energy and Mn concentrations. To understand the role of Mn on acoustic phonon contribution to the resistivity of the reference material two dimensional GaN, we have calculated the resistivity of two dimensional  $Ga_{(1-x)}Mn_xN$  alloy and presented in Figure 4. The resistivity increases similar to scattering rate but its increase is faster for higher concentration of Mn. The inset of Figure 4 also shows the variation of resistivity with Mn concentration. The calculation of total resistivity by considering all different scattering mechanism is in progress since our investigation for scattering rate and resistivity is based on the acoustic deformation potential i.e. the interaction between carrier and acoustic phonons.

**4 Conclusion**

The acoustic phonon scattering rate using the acoustic deformation potential and acoustic phonon contribution to the resistivity for the two dimensional

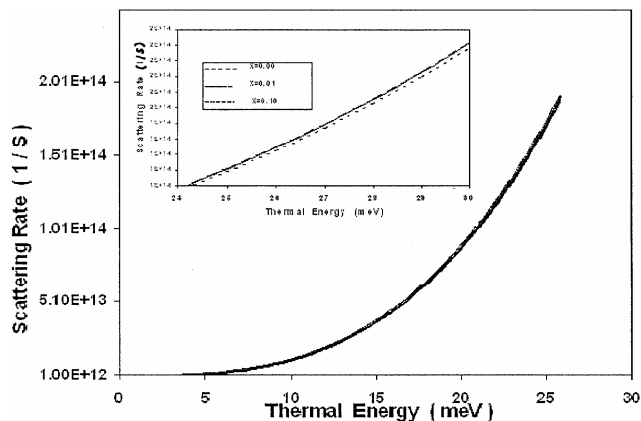


Fig. 1—Variation of acoustic phonon scattering rates for two-dimensional  $Ga_{(1-x)}Mn_xN$  with manganese concentration and thermal energy

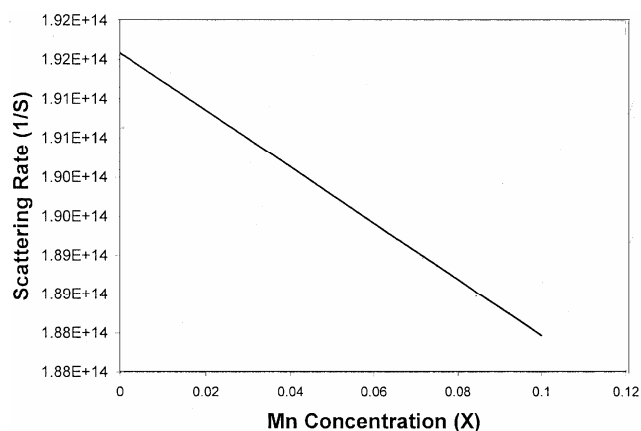


Fig. 2—Variation of scattering rate with manganese concentration

Table 1—Input parameters, effective mass and deformation potential for two dimensional $Ga_{(1-x)}Mn_xN$		
Concentration $x (\leq 0.1)$	Effective mass ( $\times 10^{-28}$ gm)	$D_A$ (in eV)
0.000	2.0020	21.61
0.001	2.0843	21.16
0.002	2.1860	20.66
0.003	2.2766	20.25
0.004	2.3720	19.84
0.005	2.5180	19.25
0.006	2.6278	18.84
0.007	2.7420	18.44
0.008	2.8998	17.96
0.009	2.9610	17.74
0.010	3.1086	17.31
0.100	13.010	08.39

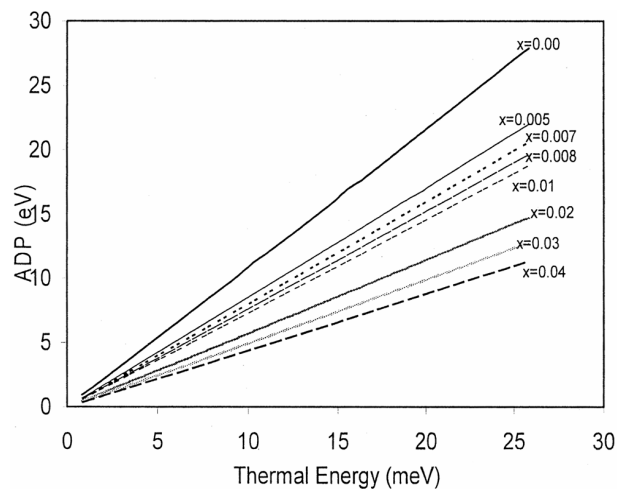


Fig. 3—Variation of acoustical deformation potential (ADP) with manganese concentration and thermal energy

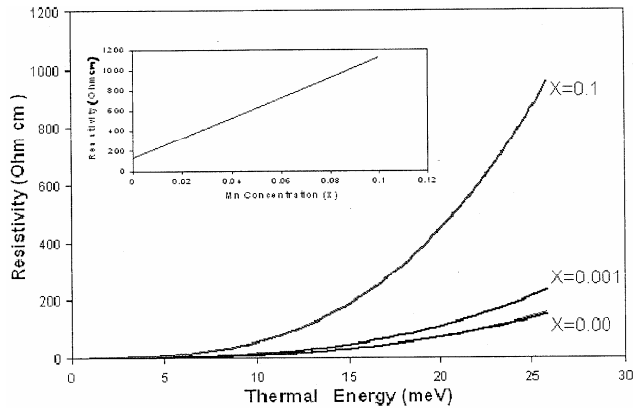


Fig. 4—Resistivity variation with respect to thermal energy and manganese concentration

$\text{Ga}_{(1-x)}\text{Mn}_x\text{N}$  quantum well for different energies and concentrations of Mn has been calculated. We observed that the temperature as well as the

concentration of manganese in GaN host influences the carrier acoustic phonon scattering rates and therefore, the resistivity varies through acoustic deformation potential.

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#### References

- 1 Kondow M, Uomi K & Niwa A, *Jpn J Appl Phys*, 35 (1996) 1273.
- 2 Kurtz S R, Allerman A A & Jones E D, *Appl Phys Lett*, 74 (1999) 729.
- 3 Chang P, Baca A & Li N, *Appl Phys Lett*, 76 (2000) 2262.
- 4 Ohno Y, *Nature*, 402 (1999) 787.
- 5 Dutta S & Das B, *Appl Phys Lett*, 56 (1990) 665.
- 6 Lundstrom M, *Fundamentals of carrier transport* (Cambridge University Press, Cambridge) 2000.
- 7 Combescot M & Bok J, *Phys Rev B*, 35 (1987) 1181.