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**Anomalous Dependence of Electron-Phonon**

**Relaxation with Carrier Concentration**

**in Graphene**

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***Abstract :*** We investigate the energy dependent electron-phonon relaxation rate of carriers in a single layer graphene and 2DEG systems through coupling to acoustic phonons interacting via the Deformation potential in the Boltzmann transport equation approach in the Bloch Gruneisen Limit. We find that in graphene the relaxation rate possesses much higher value as compared to a 2DEG system but on increasing the carrier concentration the relaxation rate is found to decrease in graphene in contrast to the 2DEG system. The full numerical computation of the4equati3o8ns reveal that the power exponent is affected with the power exponent changed from T to T⋅3.83 at the temperature 60K.

***1. Introduction :*** Since its discovery, graphene, a single sheet of carbon atom arranged in hexagonal lattice, has attracted much attention due to its novel electronic/thermal/optical/mechanical/chemical and transport properties[2, 5, 6]. It has been a very fascinating material both to the experimentalists and theoreticians as it exhibits on one hand remarkable physical properties which can be exploited for futuristic nano device applications and on the other hand it is a novel system which is also interesting from fundamental physics point of view so as much that it acts as a bridge between high energy physics and condensed matter physics. Two unique features of this strange two dimensional system are its linear energy dispersion and the chirality of electrons. The linear energy dispersion propels electrons to imitate relativistic particles with zero rest mass. Due to these features the properties of graphene differ from other conventional two dimensional systems.

 The transport properties of graphene have also been widely investigated where topical reviews have also come up[1]. The scattering mechanisms are important for understanding the transport of carriers. Usually, the Boltzmann transport equation is the first choice for a transport calculation. In graphene the Fermi surface is small and hence the limit for the temperature dependent scattering of electrons due to phonon between high temperature and low temperature range is not set by the Debye temperature but rather by Bloch-Gruneisen temperature[3]. This is because graphene is an unusually very stiff material and therefore has a very high Debye temperature of about 2800K. As the Fermi surface is small in grapheme therefore only a small percentage of phonons having can scatter electrons. These phonons have a much reduced characteristic temperature and are all populated above the Bloch- Gruneisen temperature given by , where υs is the speed of sound, is the Fermi wave vector and other symbols have usual meaning. In the BG regime the relaxation rate calculated from the Boltzmann transport after neglecting terms in the calculation has been reported to vary as T4, which is the same as a two dimensional electron gas 2DEG behaviour. Since obtaining analytical result in general places severe restrictions for getting a closed form solution and hence sometimes there are chances that significant physics could be lost in the process.

 We find that in the case of calculation of relaxation time in graphene reported in the literature [4], the approximations made in obtaining the solution in the BG regime have altogether neglected the contribution of the chirality term which is special feature of graphene and which also distinguished it from conventional 2DEG. Hence, the behavior for a single layer grapheme (SLG) and a 2DEG system is similar. We, therefore in this paper invoke full numerical computation to obtain the results and analyze the subsequent features. We have considered only the role of longitudinal acoustic phonons only in the calculation of energy dependent relaxation rate and the other couplings due to optical phonons are ignored because either they are very weak or ineffective to provide the significant scattering. Therefore in the light of above arguments we calculate the energy dependent relaxation rate in graphene and 2DEG systems numerically in the Boltzmann transport formalism and determine the relaxation rate exponents as a function of temperature and carrier concentration and compare the results. l electronic applications[3, 4].

***2. Brief Formalism :*** In this work, we calculated the energy dependent relaxation rate in graphene and 2DEG systems limited only by acoustic phonons scattering. The Boltzmann transport theory is used to calculate the acoustic phonon scattering limited relaxation rate both in graphene and a conventional 2DEG system. The energy dependent relaxation rate is given by [4],

 (1)

where is the scattering angle between the incoming and outgoing wave vectors k and k’, is the Fermi distribution function with µ as the finite temperature chemical potential,is the transition probabilityfrom the state with momentum *k* to state k’ and has the form [4]

 (2)

where is the matrix element for scattering by acoustic phonon. The for SLG and 2DEG are respectively given by the following equations;

 (3)

In eq.(3) there is an additional factor of in SLG called the chirality factor, that arises in the matrix element of SLG due to change in the overlap between different orbitals placed on different atoms, is the deformation potential coupling constant, m is the electronic effective mass, ρ is the areal mass density, A is the sample area. The term in eq.(2) is given by

 . (4)

In which is the acoustic phonon energy with the phonon velocity and the Bose distribution function of acoustic phonons at lattice temperature i.e. phonon occupation number. The first term and second terms respectively in eq. (4) take care of the absorption and emission of an acoustic phonon of wave vector . In the BG regime and after feeding the values of the terms from eqs. (2) ,(3) and (4) in eq. (1) one obtains for SLG

 (5)

where is the Fermi wave vector of SLG, is the Fermi velocity of electrons and is given by the following equation,

 (6)

In terms of new variables the eq. (5) for SLG can be cast into the following form;

 (7)

Similarly for 2DEG the eq. (1) takes the form

 (8)

The equation (7) for SLG is the unscreened relaxation time which yields a simple analytical power law solution in the Bloch Gruneisen (BG) regime, where q«2kF and which for the ease of reference is quoted [4];

 (9)

in which is the Riemann zeta function of order 4.

In case of 2DEG systems, the evaluation of unscreened relaxation time, eq.(8), under the BG approximation, yields the following solution;

 (10)

***3****.* ***Results and Discussion :*** Though eqs. (7) and (8) are not solvable analytically in the most general case but numerical solution can be obtained. To figure out the un approximated version of the solution of eqs. (7) and(8) we solved these equations numerically and worked out their temperature and carrier concentration dependencies. The numerical calculations have been done using the following parameters- m\*=0.033m0, *D*=19 eV, =5.7, vs=2× 106 cm/sec, = 1 ×108 cm/sec, N=0.5n,1.0n 2.0n with n= 1 1012 cm-2, ρ=7.6 ×10-8 gm/cm . In fig. 1 we plotted the relaxation rate vs temperature for SLG from eq. (7) at different values of carrier concentration as given in the caption to fig.1. We find that the relaxation time increases with temperature and the temperature power exponent changes from the analytical behaviour to T3.83 at 60K. Further it can be observed from fig.1 that the relaxation time decreases on increasing the values of carrier concentration. We have shown the analytical result for SLG from eq. (9) in fig.2A and the numerical results from eq. (7) in fig. 2B, when relaxation rate is plotted with carrier concentration for different values of temperature in SLG. It can be noticed from figs. 2A and 2B that the relaxation time decreases with increasing concentration for both analytical and numerical results but the decline is steeper for the analytical curves of fig.2A. The behavior noted in fig.2B (that is decline in relaxation time with increase in concentration and increase in relaxation time with increase in temperature) corroborates the behavior observed in fig.1 for numerical result. In fig. 3 we plotted the relaxation time for a 2DEG system from eq. (8) at different carrier concentration as given in the caption to the fig. 3. Comparing fig. 3 and fig. 2 we notice that the relaxation time increases in fig. with increase in carrier concentration for a 2DEG - which is in marked contrast to the behavior noted for SLG from fig. 2. This is because of the chirality factor which affects the relaxation rate in graphene and makes it behave anomalously as regards to conventional 2DEG systems. To ascertain further the behavior noted in fig. 3, we have plotted the variation of relaxation rate with carrier concentration for different values of temperature for the analytical case and numerical case for a 2DEG system in figs. 4A and 4B, respectively. These two contrasting figures clearly exhibit the strikingly different dependence of relaxation time in SLG and conventional two dimensional systems and this is all because of the special chiral behavior of relativistic electrons in graphene which define the novel transport properties of SLG. Further it can be concluded that from the numerical study that that the approximation that we generally make to obtain the analytical results cannot capture the whole behavior and a numerical computation becomes essential to observe the properties of system appropriately.



***Figure – 1 :*** Graphene Relaxation Rate vs Temperature for different values of concentration, given by equation (7). Curve A is the numerical result for N=0.5n, curve B is for N=1.0n, Curve C is for N=2.0n (where n.



1. **(B)**

***Figure – 2 :*** Graphene Relaxation Rate vs Concentration for different values of temperature. Fig. 2(A) is for analytical result and 2(B) is for numerical result. Curve A is for T=5K, curve B is for T=20K, Curve C is for T=60K.



***Figure – 3 :*** 2DEG system Relaxation rate vs Temperature for different values of concentration, given by equation (8). Curve A is the numerical result for N=0.5n, curve B is for N=1.0n, Curve C is for N=2.0n (where n.

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 **(A) (B)**

***Figure – 4 :*** 2DEG system Relaxation Rate vs concentration for different values of temperature. Fig. 4(A) is for analytical result and 4(B) is for numerical result. Curve A is for T=5K, curve B is for T=20K, Curve C is for T=60K.

***4. Conclusions :*** The dependency of the relaxation rate on carrier concentration is strikingly different in graphene as compared to other two dimensional electron gas systems. That is decline in relaxation time with increase in concentration in graphene and increase in relaxation time with increase in concentration in conventional 2DEG. This is because of the chirality factor of graphene which affects its relaxation rate and other transport properties. The numerical computation of the relaxation time yields a different temperature, dependency in the Bloch Gruneisen limit, from the analytical T4 behaviour to the numerical behaviour at 60K. So it can also be concluded from the numerical study that the approximation that we generally make to obtain the analytical results cannot capture the whole behavior and a numerical computation becomes essential to observe the properties of system appropriately.

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