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Amplification of Acoustic Phonons in Dirac Semimetal Cd_3As_2 with degenerateenergy dispersion

Kasala Suresha
Department of Physics, Government First Grade College, Hosadurga – 577 527, Karnataka

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ABSTRACT: At close to Fermi level with degenerate energy dispersion hypersound sound amplification/attenuation of acoustic phonons in 3-dimensional Dirac Semimetal Cd_3As_2 was theoretically studied. When (V_d/V_s) is greater than one, where $V_d$is electron drift velocity and V_s is sound velocity, the amplification was obtained and for (V_d/V_s) is less than one, the attenuation was obtained which will lead to acoustoelectric effect in Cd_3As_2. The dependence of attenuation co-efficient on (V_d/V_s) was studied resulting Cerenkov Effect similar to that of homogeneous semiconductors.

I. INTRODUCTION:

Quantum materials recently known as Weyl and 3-dimensional Dirac semimetals (3DDS) have become rapidly growing materials in experimental and theoretical [1-5] research because they exhibit linear energy dispersion relation. The 3DDS are considered to be analogue of Graphene and have gapless band feature with linear band dispersion and vanishing effective mass in low energy states. The 3DDS such as Cadmium Arsenide (Cd_3As_2) has drawn more interest as it is chemically stable compound in air with very high mobility [6-8]. This Cd_3As_2 exhibit many anomalous transport properties such as strong quantum oscillations [7,9], ultrahigh mobility [6,10] and very high magneto resistance [10,11]. Also Cd_3As_2 has important role in photonic devices such as infrared photodetector [12] and optical switching mechanism for the mid-infrared photodetector [13]. Since 3DDS have inherent zero energy gap and linear band dispersion, can absorb photons in the complete Infrared region. The 3DDS have advantage over 2D Dirac Semimetals like monolayer of Graphene because bulk nature of 3DDS enhances the efficiency of photon absorption. For Cd_3As_2, mobilities [6-8,14] and resistivity [7] are measured experimentally and theoretically studied for electron transport properties [15,16].

In this article, we studied amplification/attenuation of acoustic phonons in Cd_3As_2 when an acoustic phonon propagates through a metal, electron-phonon interaction phenomenon exchange the momentum and energy between electron and acoustic waves, leads to amplification/attenuation of acoustic phonons. During the electron-phonon interaction phonon gives up not only energy but also momentum to the electrons. This net gain momentum of electrons in the direction of propagation and this change of momentum leads to dc force acting on the electrons which can be looked upon as an acoustoelectic effect. Earlier this idea of acoustoelectric effect has been studied in early fifties in metals [17], low-dimensional semiconductors [18-22] and recently in Graphene Nano Ribbon (GNR) [23]. According to Cerenkov condition, when $V_d>V_s$, number of phonons would gradually grow exponentially [21] leads to amplification of acoustic phonons or when $V_d<V_s$ leads to attenuation or absorption of acoustic phonons. This amplification/attenuation of acoustic waves is proven to be very useful tool for the breakdown of quantum hall effect [24], the generation of coherent phonon polariton radiation [25], high gain in coherent acoustic oscillator in semiconductors [26] and amplification of ultrasonic waves in GaN [27].

Further, the emission and absorption of acoustic phonons can be used to provide phenomenon such as high electron mobility, terahertz (THz) hypersonic sources for the phonon laser or SASER [28,29]. There is an experimental evidence for surface acoustic wave amplification in graphene [30] and also theoretical evidence for possibility of attaining Cerenkov acoustic phonon emission in graphene [31,32]. Komirenko et al [33] have provided the analysis for amplification of acoustic phonons in confined quantum well structures and electrical method for coherent phonon generation in GaAlAs quantum well heterostructures.

Experimentally it is observed that when $V_d = 0$, there will be no attenuation of acoustic phonons [31]. This experimental work motivates the theory that can lead to the attainment of SASER in 3DDS for use of non-destructive testing of acoustic scanning system and microstructure and also for the generation of high frequency elastic oscillations in phonon spectrometer.

1. Theory:

With the assumption in short-wave region $ql \gg 1$ (where q is acousticwave number and l is electron mean free path) the probability transition due to electron-phonon interaction using Golden rule is given by [22]

$$\frac{dN_q}{dt} = \frac{2\pi}{\hbar} g \sum_{k\,k'} |M(q)|^2 \{(N_q + 1)\ f(E_k + \hbar wq 1 - fEk - Nq \quad fEk1 - Ek + \hbar wq\ \delta(Ek+q-Ek-\hbar wq) \quad (1)$$

where$g = g_s x g_v$ with g_s is spin degeneracy and g_v is valley degeneracy. N_q represents the number of phonons with a wave vector $\mathbf{q}$ and $(N_q\ +1)$ accounts for th presence of $N_q$phonons in the system when additional phonon is emitted. $f(E_k)\ [1 - f(E_k + \hbar w_q)$represent the probability that initial state $\mathbf{k}$ is occupied and final state $\boldsymbol{k}' = \boldsymbol{k}+\boldsymbol{q}$ is empty whilst the factor $N_q\ f(E_k)[1 - fEk+\hbar wq$ is that of the Boson and Fermion statistics.$|M(q)|^2$ is the electron-phonon matrix element, $\hbar w_q$ is acoustic phonons energy characterized by phonon frequency w_q.

The unperturbed drifted electron distribution function described by electron temperature T_e is given by

$$f(E_k) = \left[exp\left\{-\frac{1}{k_B T_e}\varepsilon\ (k - mV_d)\right\} - \chi\right]^{-1} \quad (2)$$

with k being the electron momentum and χ is the chemical potential, V_d is the electron drift velocity relative to lattice site. K_B is Boltzmann constant. In equation (1), converting summation over k, k' into integrals and by assuming that $N_q \gg 1$, yields

$$\frac{dN_q}{dt} = \alpha_q N_q$$

Using electron-phonon matrix element, the attenuation co-efficient is given by

$$\alpha_q = \frac{AD^2\hbar q}{(2\pi)^3 \hbar V_F \rho V_s}\int_0^\infty kdk \int_0^\infty k'dk' \int_0^{2\pi} d\varphi \int_0^{2\pi}\left\{\left[f(E_k) - f(E_k + \hbar\omega_q)\right]\delta\left(E_k - (E_k + \hbar\omega_q) - \frac{1}{\hbar V_F}(\hbar\omega_q - V_d.\hbar q)\right)\right\} d\theta \quad (3)$$

whereA is area of 3D diracsemimetal, D is acoustic deformation potential, $\rho$is density of weyl semimetal. At low temperature, $k_B T_e \ll 1$, the distribution function becomes$f(E_k) = exp\left(-\frac{\epsilon(k)}{k_B T_e}\right)$. Then equation (3) can be expressed as

$$\alpha_q = \frac{AD^2\hbar q}{2\pi\hbar V_F \rho V_s}\int_0^\infty kdk\left(k - \frac{1}{\hbar V_F}(\hbar\omega_q - Vd.\hbar q exp - \hbar VFkkBTe - exp - \hbar VFkBTek - 1\hbar VF\ \hbar\omega q - Vd.\hbar q \quad (4)$$

Using standard integrals, equation (4) can be expressed as

$$\alpha_q = \alpha_0\left\{2 - \frac{\hbar\omega_q}{k_B T_e}\left(1 - \frac{V_d}{V_s}\right)\right\}\left[1 - exp\left(-\frac{\hbar\omega_q}{k_B T_e}\left(1 - VdVs \quad (5)\right.\right.\right.$$

$$\text{where}\ \alpha_0 = \frac{AD^2 (k_B T_e)^3 q}{2\pi\hbar^3 V_F^4 \rho V_s} \quad (6)$$

2. Cerenkov condition (Phonon amplification)

By recalling that when $E_k < E_{k+q}$, yields $f(E_k) > f(E_k + \hbar w_q)$ then the amplification co-efficient α_q is greater than zero for $(w_q - V_d q) > 0$ and less than zero for $(w_q - V_d q) < 0$. During amplification the number of acoustic phonons would gradually grow exponentially. Therefore the criterion for the onset of phonon instability (amplification) is just the “Cerenkov Condition” $(w_q - V_d q) < 0$ or $V_d > V_s$ [22].

3. Results and Discussion:

The final expression (5) is analysed numerically for Cd_3As_2 at T = 5.0 K using the parameters D = 20eV, $V_s = 2.3\text{x}10^3$ m/s, $V_F = 10^6$ m/s, $\rho = 7\text{x}10^3\ \text{Kg/m}^3$ [34].The electric field can be calculated using $E = \frac{V_d}{\mu}$. At low temperature (~ 5K) the electron mobility in Cd_3As_2 μ =$9.0\text{x}10^6$ cm^2/Vs. [6-8, 14] gives the electric field E = 0.0281 V/cm. Figure 1 shows the variation of $\frac{\alpha_q}{\alpha_0}$ with applied electric field at $V_d = 1.1\ V_s$. It is observed that. At lower electric field, $\frac{\alpha_q}{\alpha_0}$ is almost constant (absorption) and at E = 0.03 V/cm and above, the amplification takes place.

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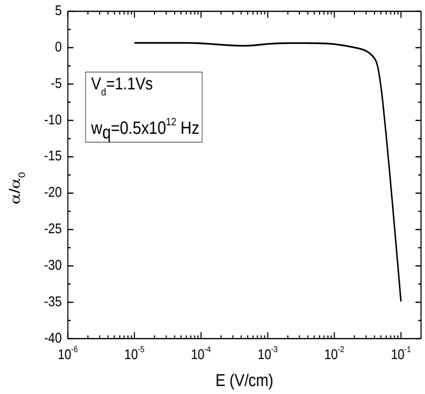

Figure 1: Amplification co-efficient as a function of electric field.

In Figure 2, the dependence of $\frac{\alpha_q}{\alpha_0}$ on $\frac{V_d}{V_s}$ is analysed for different phonon frequencies w_q. From the graph, when $V_d > V_s$ gives rise to an amplification of acoustic phonons, the same amplification process also occurs in case of quantum well wires [21] and in Graphene [35]. However, for $V_d < V_s$, an absorption of acoustic phonons was observed. Figures 3 and 4 shows the 3D representation ofamplification of phonons for w_q = 0.5 THz and 1.0 THz respectively. In Figure 3, maximum amplification $\frac{\alpha_q}{\alpha_0}$ = 0.66 takes place at $V_d = V_s$ =0 but in Figure 4, maximum amplification $\frac{\alpha_q}{\alpha_0}$ = 0.66 takes place at V_d = 0.5 V_s.

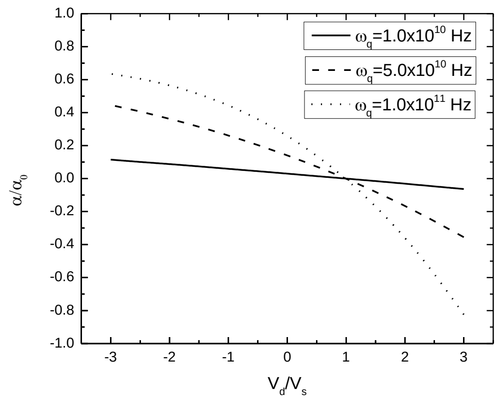

Figure 2: Variation of amplification co-efficient against (V_d/V_s) for different w_q.

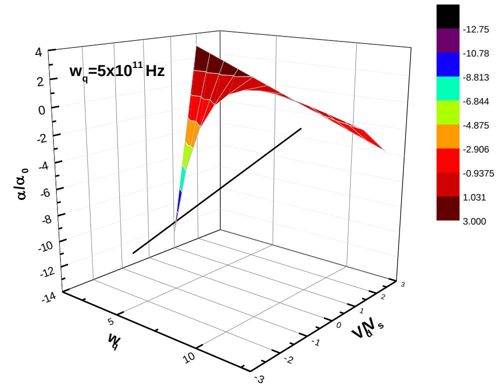

Figure 3: 3D graph of variation of $\frac{\alpha_q}{\alpha_0}$ with $\frac{V_d}{V_s}$

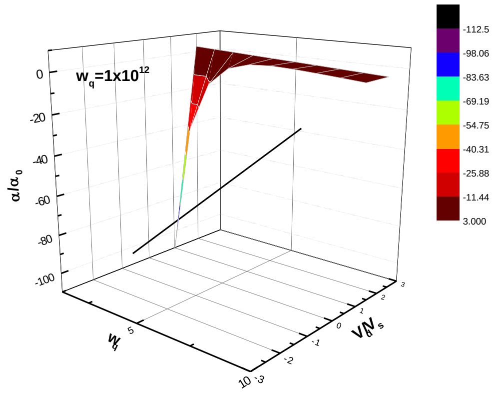

Figure 4: 3D graph of variation of $\frac{\alpha_q}{\alpha_0}$ with $\frac{V_d}{V_s}$

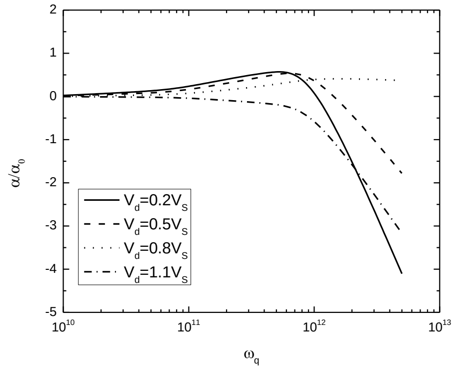

Figure 5: Variation of amplification co-efficient against wq for different V_d.

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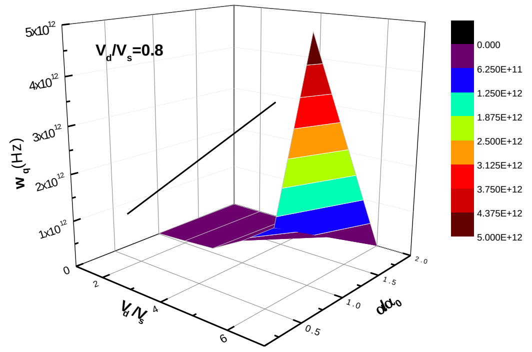

Figure 6: 3D graph of variation of $\frac{\alpha_q}{\alpha_0}$ with w_q.

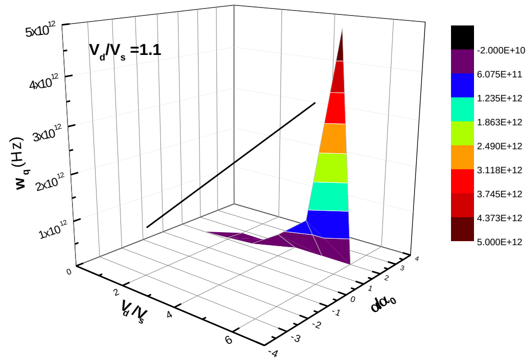

Figure 7:3D graph of variation of $\frac{\alpha_q}{\alpha_0}$ with w_q.

In Figure 5, the graph for the dependence of $\frac{\alpha_q}{\alpha_0}$ on w_q is plotted for different values of V_d. When $V_d<V_s$, we can observe the absorption of phonons and when $V_d>V_s$, amplification of phonons can be obsereved. To enhance the observed amplification or absorption, we plot 3D graph for $V_d/V_s = 0.8$ and $V_d/V_s = 1.1$ in Figures 6 and 7. Maximum amplification take place at $w_q = 1.0$ THz for $V_d/V_s = 0.8$ and for $V_d/V_s = 1.1$.

II. CONCLUSION:

In this article we theoretically studied theory of amplification/attenuation of acoustic phonons in 3DDS Cd_3As_2 considering the case of electron-acoustic phonon interaction at low temperature with degenerate energy dispersion. With the assumption of shifted Fermi-Dirac distribution function, we studied amplification co-efficient as a function of drift velocity and frequency. We observe that amplification can take place when $V_d>V_s$. We also studied the effect of amplification co-efficient over electric field, frequency and drift velocity. With this work hypersound studies in Cd_3As_2 enlighten a much better source of high phonon frequencies than that of homogeneous low dimensional semiconductors.

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