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Acoustoelectric effect in Graphene with degenerate energy dispersion

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Abstract

The acoustoelectric effect AE in Graphene with degenerate energy dispersion is theoretically studied for hypersound in the regime $ql >> 1$. At low temperatures ($k_\beta T << 1$), the non-linear dependence of Acoustoelectric current j/j_0 on the frequency ω_q and temperature T are numerically analysed. The obtained graph for j/j_0 against ω_q qualitatively agreed with an experimentally obtained results. For j/j_0 versus T, the dependence of Acoustoelectric current in Graphene was found to manifest at low temperatures.

Key Words: Acoustoelectric effect, Graphene, Fermi-Dirac distribution

Introduction

In semiconducting materials, the need to acoustically generate d.c current for scientific applications has generated much interest. This phenomena is referred to as Acoustoelectric effect AE and it involve the transfer of momentum from phonons to conducting charge carriers which leads to the generation of d.c. current in the sample. Acoustoelectric effect (AE) in Bulk

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and Low-dimensional semiconducting materials has been extensively studied both experimentally [1, 2, 3, 4, 5, 6, 7] and theoretically [8, 9, 10, 11]. Recently, AE studies in Nano materials such as Graphene [12, 13, 14, 15, 16] and Carbon Nanotube (CNT) [17, 18, 19, 20] has attracted special attention. This is due to the remarkable electrical and mechanical properties of these materials especially the extreme electron mobility which persist at room temperatures. This makes Graphene and Carbon Nanotubes CNT suitable for applications in electronic systems such as light storage in quantum wells [21], generating single electrons [22] and photons, particularly for quantum information processing [23, 24, 25] and for inducing charge pumping in nanotube quantum dots. Experimentally, AE studies has been reported in Graphene [26, 27, 28, 29] but till date no theoretical analysis is reported. In this paper, the theoretical analysis of Acoustoelectric Effect AE in Graphene in the hypersound regime $ql >> 1$ (where q is the acoustic wave number, l is the mean free path of an electron) is carried out. The general expression is analysed numerically for various frequencies, and temperatures. The paper is organised as follows: In theory section, the theory underlying the Acoustoelectric effect in Graphene is presented. In the numerical analysis section, the final equation is analysed and presented in a graphical form. Lastly, the conclusion is presented in section 4.

Theory

We will proceed following the works of [13, 15], the Acoustoelectric Current in Graphene is given as

$$j_{\vec{ac}} = -\frac{e\tau A|C_q|^2}{(2\pi)^2 V_s}\int_0^\infty kdk\int_0^\infty k'dk'\int_0^{2\pi} d\phi\int_0^{2\pi} d\theta\{[f(k)-f(k')]\times V_i\delta(k-k'-\frac{1}{\hbar V_F}(\hbar\omega_q))\} \quad (1)$$

with $k' = k - \frac{1}{\hbar V_F}(\hbar\omega_q)$. For accoustic phonons, $C_q = \sqrt{|\Lambda|^2\hbar q/2\rho\hbar\omega_q}$, Λ is the constant of deformation potential, ρ is the density of the graphene sheet. τ is the relaxation constant, V_s is the velocity of sound, and A is the area of the graphene sheet. Here the acoustic wave will be considered as phonons of frequency (ω_q) in the short-wave region $ql >> 1$ (q is the acoustic wave number, l is the electron mean free path). The linear energy dispersion $E(k) = \pm\hbar V_F|k|$ (the Fermi velocity $V_F \approx 10^8 ms^{-1}$) at the Fermi level with low-energy excitation. From Eqn.(1), the velocity $V_i = V(k') - V(k)$. Differentiating the energy dispersion yields

$$V_i = \frac{2\hbar\omega_q}{\hbar V_F} \quad (2)$$

At low temperature $k_BT << 1$, the Fermi-Dirac distribution function become

$$f(k) = exp(-\beta(\varepsilon(k))) \quad (3)$$

Inserting Eqn.(2) and Eqn.(3) into Eqn.(1) gives

$$j_{\vec{ac}} = -\frac{2A|C_q|^2\tau\hbar\omega_q}{(2\pi)^3\hbar V_F V_s}\int_0^\infty kdk(k-\frac{1}{\hbar V_F}(\hbar\omega_q))[exp(-\beta\hbar V_F k) - exp(-\beta\hbar V_F(k-\frac{1}{\hbar V_F}(\hbar\omega_q)))] \quad (4)$$

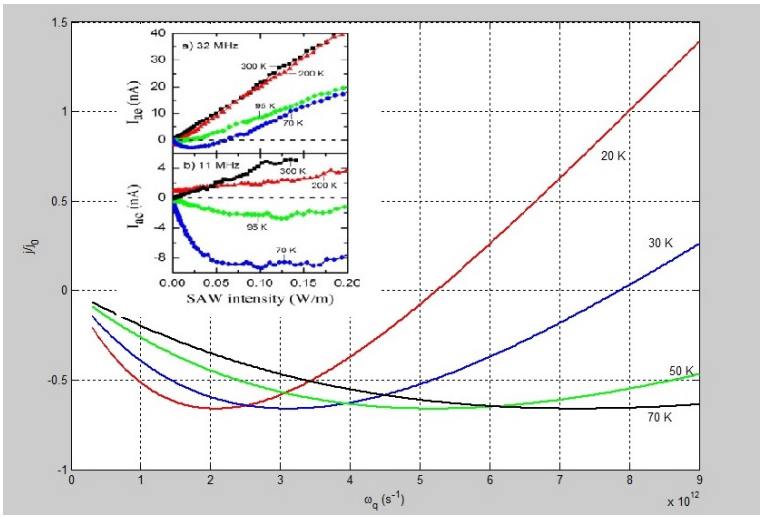

Figure 1: (a) Dependence of j/j_0 on ω_q for varying T. Insert: Dependence of Acoutoelectric Current (I_{ae}) on SAW intensity for varying T [27].

Using standard integrals in Eqn(4) and after a cumbersome calculation yields the Acoustoelectric Current (j_{ac}) as

$$j_{ac} = j_0\{2 - \beta\hbar\omega_q\}[1 - exp(-\beta\hbar\omega_q)] \tag{5}$$

where

$$j_0 = -\frac{2\tau A|\Lambda|^2 kT\hbar q}{(2\pi)^3\beta^3\hbar^4 {V_F}^4 \rho V_s} \tag{6}$$

Numerical Analysis

The Eqn (5) is analysed numerically for a normalized graph of j/j_0 against ω_q and T. The following parameters were used $\Lambda = 9eV$, $V_s = 2.1\times10^6 cms^{-1}$ and $\vec{q} = 10^5 cm^{-1}$. In Figure 1, the graph for the dependence of j/j_0 on ω_q for varying T is plotted. From the Figure (1), the non-linear graph of Acoustoelectric current j/j_0 decreases with an increase in temperature. The insert

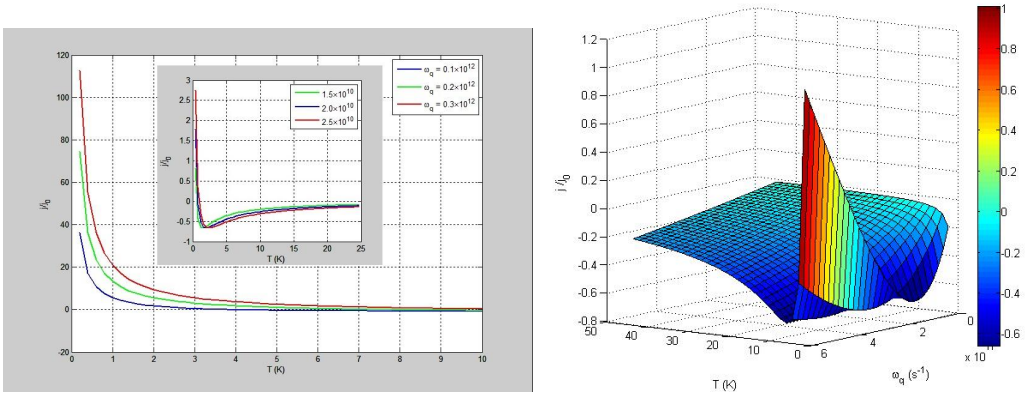

Figure 2: (a) Dependence of j/j_0 on temperature T on varying $\omega_q(10^{10})$, insert was plotted with $\omega_q(10^{12})$, (b) A 3D graph of the dependence of j/j_0 on ω_q and T

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is an experimentally obtained results of acoustoelectric current versus Surface Acoustic Wave (SAW) intensity. For acoustic phonons, the intensity is proportional to the frequency of the acoustic phonon $i.e. I = \hbar\omega_q flux$. Therefore, the theoretically obtained graph (see Fig. 1) qualitatively agrees with that obtained experimentally by Bandhu and Nash [27]. The acoustoelectric current j_{ac} relates the hypersound absorption Γ as

$$j^{ac} = \frac{-2e\tau}{\hbar V_F}\Gamma \tag{7}$$

which is the Weinreich relation [31]. In Figure 2, the dependence of acoustoelectric current j/j_0 on temperature T is plotted with varying ω_q. At $\omega_q = 10^{12}$, the acoustoelectric current decreases sharply to a minimum point and remain constant but at $\omega_q = 10^{10}$ (see insert graph), the graph decreased pass the $j/j_0 = 0$ point to a minimum then raises to a constant values. For better understanding of the relation between j/j_0, ω_q and T, a 3D graph was plotted (See Figure 2b). In the Figure 2b, the maximum point point,

$T = 1.5K$, $\omega_q = 6 \times 10^{11} s^{-1}$ and $j/j_0 = 1.006$. At the minimum point, $T = 1.5K$, $\omega_q = 1.2 \times 10^{11} s^{-1}$ and $j/j_0 = -0.635$.

Conclusion

The Acoustoelectric effect in Graphene is studied in the hypersound regime $ql >> 1$. At low temperatures , the theoretically obtained Acoustoelectric current j/j_0 qualitatively agreed with an experimentally obtained results.

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