Acoustoelectric Effect in degenerate Carbon Nanotube

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Abstract

Acoustoelectric Effect $AE$ in degenerate Carbon Nanotube (CNT) was theoretically studied for hypersound in the regime $ql \gg 1$. The dependence of acoustoelectric current $j^{ac}$ on the acoustic wave number $\vec{q}$ and frequency $\omega_q$ at $T = 10K$ and scattering angle ($\theta > 0$) was evaluated at various harmonics $n = \pm 1, 2, \ldots$ (where $n$ is an integer). In the first harmonics ($n = \pm 1$), the non-linear dependence of $j^{ac}$ on $\omega_q$ and $\vec{q}$ were obtained. For $n = \pm 2$, the numerically evaluated $j^{ac}$ qualitatively agreed with an experimentally obtained result.

Keywords: Carbon Nanotube, Acoustoelectric, degenerate, hypersound

Introduction

Carbon Nanotubes (CNT) discovered by Iijima \cite{Iijima1991} are emerging as important materials for electronic applications due to their remarkable electrical and mechanical properties \cite{Iijima1992, Dresselhaus2000, Dresselhaus2001}. The metallic and semiconducting Single-Walled Carbon Nanotube (SWCNT) have been proposed as the most viable materials to develop high performance thin films to completely eliminate the

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use of critical metals in electronic devices such as: i) Indium in transparent conducting films (TCF, indium oxide doped by tin, ITO) and ii) Indium and Gallium as semiconductor $\text{InGaZnO} (a-\text{IGZO})$ in thin film field effect transistors (TFTs) for applications in optoelectronics \cite{5,6,7,8,9}. The unusual band structure \cite{10,11,12} of CNT, coupled with large electron densities and high drift velocities (with electron mobility of $\mu \approx 10^5 \text{cm}^2/\text{Vs}$) at room temperatures opens a way for employing carrier control processes rather than direct electrical control \cite{13}. In the linear regime, electron-phonon interactions in CNT at low temperatures leads to emission or absorption of large number of coherent acoustic phonons \cite{14,15,16}. When the momentum of the acoustic phonons is absorbed by the conducting electrons, it leads to the appearance of $d.c$ electric field \cite{17,18,19,20,21}. This phenomena is known as Acoustoelectric effect $AE$ \cite{22,23,24,25,26}. Studies of Acoustoelectric effect in bulk materials such as Gallium Nitride ($\text{GaN}$) \cite{27,28,29} with applications in $\text{GaN}$ film bulk acoustic resonators (FBARs), Indium Antimonide \cite{30} and $\text{GaAs}/\text{LiNbO}_3$ \cite{31} has being reported.

With the advent of low-dimensional materials, $AE$ has been intensively studied in quantum wells \cite{32} to produce quantized current in $1-D$ channels \cite{33} for light storage and to induce charge pumping in nanotube quantum dots \cite{34}. $AE$ studies in superlattices \cite{35,36}, quantum wires \cite{37,38} and Zinc Oxide ($\text{ZnO}$) Nanowires \cite{39} has been reported. Recently, the need for acoustically driven current flow in semiconductor nano-structures has received particular attention as a means of generating or controlling single electrons and photons for quantum information processing \cite{40,41,42}. From the hypersound absorption \cite{43} studies conducted on CNT, it was found that
CNT exhibit good AE effect but till date, there is no general analytical theory of Acoustoelectric effect in CNT. However, a few experimental work by Ebbecke et. al [44] and Reulet et. al [45] in CNT has been carried out. In this paper the theoretical treatment of AE in CNT in the hypersound regime \( ql \gg 1 \) (where \( q \) is the acoustic wave number, \( l \) is the mean free path of an electron) is carried out. The general expression obtained is analysed numerically for harmonics \( n = \pm 1, \pm 2 \) (where \( n \) is an integer). The paper is organised as follows: In section 2, the kinetic theory based on the linear approximation for the phonon distribution function is setup, where, the rate of growth of the phonon distribution is deduced and the acoustoelectric current \( (j^{ac}) \) is obtained. In section 3, the final equation is analysed numerically in a graphical form at various harmonics. Lastly the conclusion is presented in section 4.

1. Theory

Proceeding from [22, 23], the Acoustoelectric current \( j^{ac} \) in the hypersound regime \( ql \gg 1 \) is given as

\[
j = -\frac{4\pi\tau e}{(2\pi)^3}|C_q|^2 \int_{0}^{\infty} v_i[f(p + q) - f(p)]\delta(\varepsilon(p + q) - \varepsilon(p) - \hbar\omega)d^3p \tag{1}
\]

where the velocity \( v_i = v(p + q) - v(p) \), \( f(\varepsilon(p)) \) is the distribution function, \( p \) is the momentum of electrons and \( \tau \) is the relaxation constant. The linear energy dispersion \( \varepsilon(\vec{p}) \) relation for the CNT is given as [46]

\[
\varepsilon(\vec{p}) = \varepsilon_0 \pm \frac{\sqrt{3}}{2\hbar} \gamma_0 b(\vec{p} - \vec{p}_0) \tag{2}
\]

The \( \varepsilon_0 \) is the electron energy in the Brillouin zone at momentum \( p_0 \), \( b \) is the lattice constant , \( \gamma_0 \) is the tight binding overlap integral (\( \gamma_0 = 2.54eV \)).
The ± sign indicates that in the vicinity of the tangent point, the bands exhibit mirror symmetry with respect to each point. After collision, \( \vec{p}' = (\vec{p} + \vec{h}q)\cos(\theta) \) is the component directed along the CNT axis. Where \( \theta \) is the scattering angle. At low temperature \( (kT << 1) \), the Fermi-Dirac equilibrium function is given as

\[
f_{\vec{p}} = \exp(-\beta(\varepsilon_{\vec{p}} - \mu))
\]  

with \( \mu \) being the chemical potential, \( \beta = 1/kT \), \( k \) is the Boltzmann constant.

Inserting Eqn.(2 and 3) into Eqn.(1), and after some cumbersome calculations yield

\[
j_{ac} = \frac{2e\pi|C_q|^2}{\hbar} \exp(-\beta(\varepsilon_0 - \chi \vec{p}_0)) \{ \exp(-\beta(\chi \eta + \vec{h}q)\cos(\theta)) - \exp(-\beta \chi \eta) \}
\]

where \( \chi = \sqrt{3}\gamma_0b/2\hbar \), and

\[
\eta = \frac{-2\hbar^2\omega_{\vec{q}} + \gamma_0b\sqrt{3}\hbar\vec{q}\cos(\theta)}{\gamma_0b\sqrt{3}(\cos(\theta) - 1)}
\]

For acoustic phonons, \( |C_q| = \sqrt{\Lambda^2\hbar q/2\rho V_s} \). Where \( \Lambda \) is the deformation potential constant and \( \rho \) is the density of the material. Taking \( \varepsilon_0 = \vec{p}_0 = 0 \), the Eqn.(4) finally reduces to

\[
j_{ac} = \frac{2e|\Lambda|^2\pi\hbar q^2}{2\pi\hbar \omega_{\vec{q}}} \exp(-\beta \chi \eta) \left\{ \sum_{n=-\infty}^{\infty} \frac{\exp(-n(\theta + \beta \chi \eta))}{I_n(\beta(\chi \eta + \hbar \vec{q}))} - 1 \right\}
\]

where \( I_n(x) \) is the modified Bessel function.

**Numerical analysis**

The analytical solution of Eqn(5) is obtained numerically and the results presented graphically. The parameters used in the numerical evaluation are:
$|A| = 9\text{eV}, b = 1.42\text{nm}, q = 10^7 \text{cm}^{-1}, \omega_q = 10^{12}\text{s}^{-1}, V_s = 4.7 \times 10^5 \text{cm s}^{-1}, T = 10\text{K},$ and $\theta > 0$. The dependence of $j^{ac}$ on the acoustic wave number ($\vec{q}$) and the frequency ($\omega_q$) at various harmonics ($n = \pm 1, \pm 2$) are presented below. For $n = \pm 1$, the non-linear graph (with an initial curve) increases sharply to a maximum then decreases to a constant minimum value (see Figure 1a). By increasing the values of $\vec{q}$, the graph shift to the right with decreasing amplitude. In Figure 1b, it was observed that at $\omega_q = 0.6 \times 10^{12}\text{s}$, the $j^{ac}$ increases to a maximum point and then falls to a minimum value. Increasing the values of $\omega_q$, shift the graph to the right. More interesting is the nature of the acoustoelectric current $j^{ac}$. At $\omega_q = 0.6 \times 10^{12}\text{s}$, the ratio of the peaks balances on both side of the $j^{ac}$ axis. At $\omega_q = 0.65 \times 10^{12}\text{s}$, the ratio of the $j^{ac}$ peaks is more towards the negative side but a reverse occurs when $\omega_q = 0.7 \times 10^{12}\text{s}$. For $n = \pm 2$ (see Figure 2 (a and b)), the graph obtained for $j^{ac}$ versus $\omega_q$ qualitatively agreed with an experimentally obtained results. In Figure 2b, it is also observed that the dependence of $j^{ac}$ on $q$ is strongly non-linear. The ratio of $\frac{j^{ac}}{\Gamma}$ (where $\Gamma$ is the hypersound absorption) in the absence of a drift velocity $V_D$ is given as

$$\frac{j^{ac}}{\Gamma} = \frac{2e\tau\gamma_0 b\sqrt{3}}{\hbar}(\cos(\theta) - 1)$$

which is the Weinreich relation and is dependent on the scattering angel $\theta$. For better understanding of the obtained graphs, a 3D graph of $j^{ac}$ versus $\omega_q$ and $\vec{q}$ are presented. For $n = \pm 1$, the ratio of the height of the peaks in the positive side of $j^{ac}$ far exceeded that in the negative side (see Figure 3a). In Figure 3b, for $n = \pm 2$, the graph showed peaks at certain intervals.
Figure 1: (a) Dependence of $j^{ac}$ on $\omega q$ at varying $\vec{q}$ (b) Dependence of $j^{ac}$ on $\vec{q}$ for varying $\omega q$

Figure 2: (a) Dependence of $j^{ac}$ on $\omega q$ at various $\vec{q}$ insert shows the experimentally obtained acoustoelectric current [44] (b) Dependence of $j^{ac}$ on $\vec{q}$ for varying $\omega q$. 
2. Conclusion

The Acoustoelectric Effect \( AE \) in a degenerate Carbon Nanotube \( CNT \) is studied for hypersound in the regime \( q_l > 1 \). A strong nonlinear dependence of \( j^{ac} \) on the acoustic wavenumber \( q \) and the frequency \( \omega_q \) are observed. The dominant mechanism for such non-linear behaviour is the Acoustoelectric Effect which give rise to the acoustoelectric current \( j^{ac} \). The analytically obtained acoustoelectric current \( j^{ac} \) qualitatively agrees with an experimentally obtained result.

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