Short Communication
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On the Einstein relation between mobility and diffusion cofficint in an active Nanostructured Materials

Abstract

It is commonly known that the speed at which contemporary switching semiconductors work much depends on the carrier degeneracy of the band. Furthermore, the relation of the diffusivity to mobility ratio of the carriers in semiconductors (referred to as DMR) is very helpful because it is more accurate than any of the individual relations for diffusivity to mobility ratio, which is thought to be the two most frequently used parameters in carrier transport in semiconductors. With n-InSb and Hg1-xCdxTe as examples of numerical calculations, we will examine DMR under strong magnetic quantization of III-V in line with the three- and two-band models of Kane, respectively, along with parabolic energy bands.

Keywords: Diffusivity to mobility ratio, magnetic quantization, III-V semiconductor

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Introduction

There has been a lot of interest in recent years in researching the many physical properties of degenerate semiconductors that follow Kane's dispersion relation and have non-parabolic energy bands. Numerous aspects that result in these semiconductors' unique properties have been discovered to be influenced by the band non-parabolicity. The last few years have seen a significant increase in interest in both new technology applications as well as their ability to elucidate novel phenomena in computational and theoretical nanoscience. The quantization of the wave vector—also known as the quantum size effect (QSE)—allows for 2D electron transport parallel to the surface in QWs, representing new physical features not present in bulk semiconductors.[1] This phenomenon is caused by the restriction of carrier motion in the direction normal to the film (let's say the z-direction). To further explore these materials' electrical characteristics, a brand-new structure called QWWs has been put out.[2]

The charge carriers can only travel in the longitudinal direction in the 1D synthetic material because the electron gas is quantized in two transverse directions.[3] The degree of freedom of the free carriers substantially reduces when the quantum well's dimension goes from 1D to 3D, and the density-of-states function switches from a stepped cumulative one to Dirac's delta function.[4,5] Because of the improvement in carrier mobility, low-dimensional heterostructures made of diverse materials are being studied extensively.[6] These characteristics make such structures appropriate for use in devices such as optical modulators,[7] optical switching systems,[8] high-speed digital networks,[9] high-frequency microwave circuits,[10] quantum well lasers,[11] and others.

In order to express the performance at the device terminals and the switching speed in terms of carrier concentration, the appropriate Einstein relation must be used. It is well known that the degree of carrier degeneracy of the band has a significant impact on how quickly modern switching semiconductors operate. Furthermore, since it is more accurate than any of the individual relations for diffusivity to mobility ratio, which are thought to be the two most frequently used parameters in carrier transport in semiconductors, the relation of the diffusivity to mobility ratio of the carriers in semiconductors (referred to as DMR) is very helpful. The diffusivity of mobility ratio in non-degenerate semiconductors is $\frac{k_B T}{e}$ although for degenerate semiconductors, Landsberg demonstrated for the first time[12] that under the condition carrier degeneracy, the DMR depends only on the band structure. Additionally, substantial research has been done on the relationship between the DMR and the screening length, its relationship with the noise power, and the several DMR formulations for degenerate semiconductors with varying band structures.[13-17]

Theoretical background

The DMR is expressed as a result of the basic analysis as

$$\frac{d}{\mu}=\frac{1}{e}\frac{n_0}{\left(\partial n_0 / \partial E_F\right)} \tag{1}$$

According to the band Kane model, the following is the equation for the electron concentration in magnetic quantization in III-V semiconductors

$$n_0=\frac{eB\sqrt{\left(2m^*\right)}}{\pi^2\hbar^2}\sum_{n=0}^{n_{\max}}\left[\Phi(n,E_F)+\frac{\pi^2k_B^2T^2}{6}\Phi''(n,E_F)\right] \tag{2}$$

Using equations (1) and (2), we get

$$\frac{d}{\mu}=\frac{1}{e}\sum_{n=0}^{n_{\max}}\left[\Phi(n,E_F)+\frac{\pi^2k_B^2T^2}{6}\Phi''(n,E_F)\right]\left[\sum_{n=0}^{n_{\max}}\left[\Phi'(n,E_F)+\frac{\pi^2k_B^2T^2}{6}\Phi'''(n,E_F)\right]\right]^{-1} \tag{3}$$

For the two-band model of Kane, equation (3) gets transformed as:

$$\frac{d}{\mu}=\frac{k_BT}{e}\frac{\sum_{n=0}^{n_{\max}}\left[\frac{1}{\sqrt{a}}\left\{\left(1+\frac{3\alpha b}{2}\right)F_{-1/2}(\eta')+\frac{3\alpha k_BT}{4}F_{1/2}(\eta')\right\}\right]}{\sum_{n=0}^{n_{\max}}\left[\frac{1}{\sqrt{a}}\left\{\left(1+\frac{3\alpha b}{2}\right)F_{-3/2}(\eta')+\frac{3\alpha k_BT}{4}F_{-1/2}(\eta')\right\}\right]} \tag{4}$$

where we have applied the formula

$$\frac{D}{D\eta}F_j(\eta)=F_{j-1}(\eta)$$

For $\alpha \to 0$ as for wide gap semiconductors, we get

$$\frac{d}{\mu} = \frac{k_B T}{e} \frac{\sum_{n=0}^{n_{max}} F_{-1/2}(\eta)}{\sum_{n=0}^{n_{max}} F_{-3/2}(\eta)} \quad (5)$$

where

$$\eta \equiv \frac{\left[E_F - (n+1/2)\hbar\omega_0\right]}{k_B T}$$

Under the condition of non-degeneracy, we know

$$F_j(\eta) \approx e^{\eta}$$

and equations (4) and (5) lead to well known result as

$$\frac{d}{\mu} = \frac{k_B T}{e} \quad (6)$$

as it should be for non-degenerate semiconductors.

Experimental advice for determining ratio of $\frac{d}{\mu}$ indirectly in degenerate semiconductors with arbitrary band structures and strong magnetic quantization.

It is widely known that only the dispersion rules can explain the thermoelectric power when there is substantial magnetic quantization.[18] The amount of thermoelectric power is expressed as

$$g = \frac{1}{eTn_0} \int_{-\infty}^{+\infty} (E - E_F) R(E) \left[\left(-\frac{\partial f_0}{\partial E}\right)\right] dE \quad (7)$$

where $R(E)$ is the total number of states and f_0 is the Fermi – Dirac function. Following Tsidilkovski[18] the equation (7) can be expressed by

$$g = \frac{\pi^2}{3en_0} k_B^2 T \frac{\partial n_0}{\partial E_F} \quad (8)$$

Using equations (1) and (2), we get

$$\frac{d}{\mu} = \frac{\pi^2 k_B^2 T}{3ge^2} \quad (9)$$

Therefore, by knowing the associated thermo-electric power, which is a quantifiable experimental quantity, we may experimentally estimate DMR for any degenerate semiconductors under strong magnetic quantization having arbitrary dispersion laws.

Discussion

For n-InSb, we have plotted DMR vs 1/B according to (Figure 1) the three- and two-band models of Kane, as well as the parabolic band model, using the appropriate equation. According to figure 1, all types of III-V semiconductors exhibit DMR oscillations because of the SdH effect. Figure 1 shows that DMR oscillates as well, despite the fact that the nature of the oscillation is very different from that seen in figure 1. We have displayed DMR vs. electron concentration for the same in Figure 2. Our experimental recommendation excludes any band parameter for constant temperature that changes inversely with thermoelectric power g in equation (9) used to determine DMR.[19,20] For each model, the only necessary value of g is the experimental value for that model. Since g declines in an oscillatory manner with increasing doping under magnetic quantization, we may infer from equation (9) that the DMR will likewise grow in an oscillating manner, as shown by Figure 2. This claim is a veiled examination of our theoretical investigation. A method for examining the band structure of degenerate semiconductors under magnetic quantization is provided by the experimental value of g.

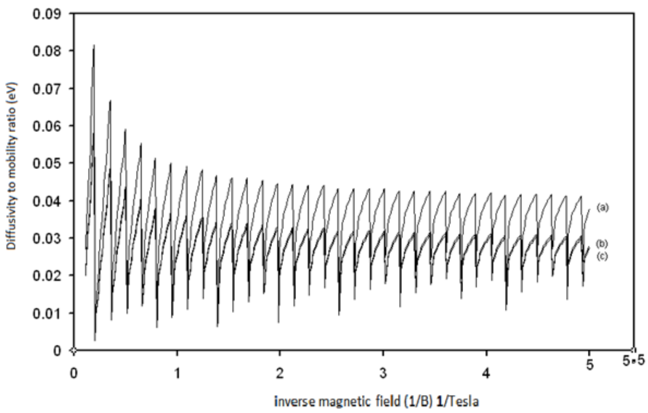

Figure 1 The plots of the DMR versus the inverse magnetic field ($1/B$) for n-InSb in accordance with (a) the parabolic band model, (b) the three-band model of Kane and (c) the two-band model of Kane respectively. ($n_o = 10^{23} m^{-3}$, $m^* = 0.0145 m_o$ and $\alpha = 4.167 (eV)^{-1}$).

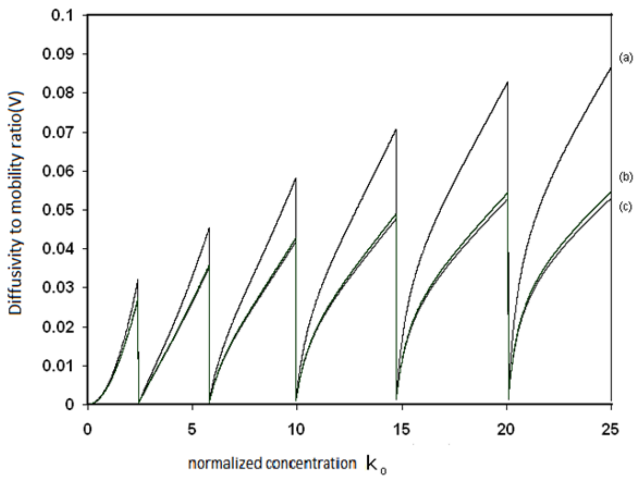

Figure 2 The plots of the DMR versus the normalized concentration (k_o) ($k_o = n_o/(10^{22} m^{-3})$, the electron concentration n_o has been expressed in m^{-3}) for n-InSb in accordance with (a) parabolic model, (b) three-band model of Kane and (c) two-band model of Kane ($B = 2 Tesla$).

Acknowledgments

None.

Conflicts of Interest

None.

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