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Shubnikov-De Haas Effect in Cylindrical Quantum Wires under the Influence of a Laser Radiation

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Abstract: Considering an infinite potential Cylindrical Quantum Wire (CQW) subjected to a dc electric field $\vec{E}_1 = (0,0,E_1)$, a Magnetic Field (MF) $\vec{B} = (B,0,0)$ and a laser radiation $\vec{E}_0 = \vec{E}\sin\Omega t$ (where E_0 and Ω are the amplitude and the frequency of the laser radiation, respectively), the quantum kinetic equation for electron distribution function is obtained. Assuming the electron gas is non-degenerate and considering the Electron - Acoustic Phonon (AP) interaction, we achieve analytical expressions for the conductivity tensor and the Hall Coefficient (HC), which are different from those for the case of the Electron - AP interaction in a Rectangular Quantum Wire (RQW) or in Two-Dimensional Electron Gas (2DEG). The Shubnikov-de Haas (SdH) oscillations will appear. The amplitudes of SdH oscillations in the dependence of Magnetoresistance (MR) decrease with increasing MF. Numerical calculations are applied for GaAs/GaAsAl CQW to show the nonlinear dependence of the HC on the frequency of the laser radiation Ω, and Magnetic Field (MF) $\vec{B}$. Wave function and energy spectrum in a CQW are dissiminar to those in other Quantum Wires (QWs). Therefore, all numerical results are different from those in the case of QWs. The most important result is that the HC reaches saturation as the magnetic field or the EMW frequency increases.

Keywords: Hall coefficient; cylindrical quantum wires; electron - optical phonon interaction; Shubnikov-de Haas oscillations.

1. Introduction

The Hall Effect in bulk semiconductors under the influence of the Electromagnetic wave (EMW) has been studied in much details [1-2]. The Hall effect is the production of a voltage difference (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and a MF perpendicular to the current. It was discovered by Edwin Hall in 1879. The HC is defined as the ratio of the induced electric field to the product of the current density and the applied MF. It is a characteristic of the material from which the conductor is made, since its value depends on the type,

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number, and properties of the charge carriers that constitute the current. In Refs [1, 2] the Hall Effect is subjected to a crossed time-dependent electric field and MF. The old Magnetoresistance (MR) was calculated when the nonlinear semiconductors were subjected to a MF and an EMW with low frequency, the nonlinearity was explained by the non-parabolicity of distribution functions of carriers. However, almost these results obtained by using the Boltzmann kinetic equation, and are limited to the case of weak MF region and high temperature. In cases of strong MF and low temperature, the Boltzmann kinetic equation is invalid. Therefore, In Refs [3] we used the quantum kinetic equation method to study the influence of an intense EMW on the HC in parabolic quantum wells with an in-plane magnetic. Numerical results show the Shubnikov-de Haas (SdH) oscillations in the MR whose period does not depend on the temperature and amplitude decreases with increasing temperature. In Refs [4] we studied the HC and the MR in Doped Semiconductor Superlattices with an In-plane MF. They are the same type SdH oscillations obtained in Two-Dimensional (2D) electron system [3, 4]. We saw earlier the conductance of a 2DEG oscillates in a MF and is periodic in 1/B where B is the flux density. There are SbH oscillations. We know that in order for these oscillations to be manifested, the electrons must be able to complete cyclotron orbits and that can happen only if the diameter of the smallest orbit $2r_c$ is smaller than the effective width of the QW. In one-dimensional (1D) electron systems, the review [5] is divided into three main subjects: Discrete states of conduction electrons confined to the vicinity of conductance of a the negatively charged acceptors, Asymmetry of plateaus in the quantum Hall effect and the SdH effect, Disorder modes in the cyclotron resonance. In Refs, [6] the SdH oscillations have observed beating in quantum wires grown on (0001) sapphire. The spin splitting of 1D electron system in quantum wire can be applied to a low-power-consuming quantum-ring interferometer. In Refs, [7] the MR and Hall resistance in a quasi-ballistic multi-terminal quantum wire of GaAs/AlGaAs heterostructure have been investigated. The SdH oscillations are observed at high MF in the absence of EMW. However, Refs [5-7] only considered the case of an absent and at the temperatures at which electron-electron and electron-impurity interactions were dominant. In a recent work [8], we studied Hall Effect in a RQW with infinitely high potential and in the presence of a laser radiation, subjected to a crossed dc electric field and magnetic field in the presence of a strong EMW characterized by electric field. The dependence of the HC under EMW in quantum wires with different directions of external fields still remains open for investigation, especially by analytical and computational methods. Therefore, in this work, calculation of the HC and Hall Conductivity in a CQW under the Influence of a Laser Radiation caused by Electron - AP interaction have been measured to investigate the SdH effect by using the quantum kinetic equation for electron. The main purpose of this is to make a comparison between our calculation and other experiments and theories. Since wave function of electron in a CQW is different from that in a RQW and 2D, probability of Electron-AP scattering, resulting in the electron form factor, changes. Energy spectra of electron in a CQW are different from those in a RQW and 2D, which bring about the conservation of momentum energy law and the scattering processes. Delta function makes a change due to all above changes. As a result, the HC and Hall conductivity in CQW differs from that in RQW and 2D. The most important difference is the MR in CQW depending on the indices n, n', l, l' (the quantum numbers of electron) and N, N' (the Landau levels) so that quantum theory of the HC and Hall conductivity in CQWs under EMW is newly developed. The work is organized as follows. In Sec. 2, we briefly describe the model of the problem and the derivation of the quantum kinetic equation for electrons in a RQW with infinitely high potential under the influence of a Laser Radiation. The expressions for Hall conductivity and the HC are presented briefly. Numerical results and discussion are given in Sec. 3. Conclusions are shown in sec. 4.

2. The Hall conductivity and the HC for Electron-AP scatterring in a CQW with infinitely high potential

We consider a CQW of the radius R and the length L with the infinite confined potential: $V(\vec{r})=0$ inside the wire and $V(\vec{r})=\infty$ elsewhere subjected to a crossed dc electric field $\vec{E}_1=(0,0,E_1)$ and magnetic field $\vec{B}=(0,B,0)$ in the presence of a strong EMW characterized by electric field $\vec{E}=(0,0,E_0\sin\Omega t)$. Hamiltonian for Electron–AP interacting system in external field can be written as:

$$H=\sum_{n,l,\vec{k}}\varepsilon_{n,l}(\vec{k}-\frac{e}{c}\vec{A}_{(t)})a^{+}_{n,l,\vec{k}}a_{n,l,\vec{k}}+\sum_{\vec{q}}\omega_{\vec{q}}b^{+}_{\vec{q}}b_{\vec{q}}+$$
$$+\sum_{n,l,n',l',\vec{k},\vec{q}}\left|C_{\vec{q}}\right|^{2}\left|I_{n,l,n',l'}(\vec{q})\right|^{2}a^{+}_{n,l,\vec{k}+\vec{q}}a_{n',l',\vec{k}}(b_{\vec{q}}+b^{+}_{-\vec{q}})+\sum_{\vec{q}}\varphi(\vec{q})a^{+}_{n,l,\vec{k}+\vec{q}}a_{n',l',\vec{k}}. \quad (1)$$

Where $a^{+}_{n,l,\vec{k}}$ and $a_{n,l,\vec{k}}$ ($b^{+}_{\vec{q}}$ and $b_{\vec{q}}$) are the creation and annihilation operators of electron (OP); $\vec{k}$ is the electron wave momentum (along the wire's axis: z axis); $\vec{q}$ is the phonon wave vector; $\omega_{\vec{q}}$ are AP frequencies; $C_{n,l,n'n'}(\vec{q})=C_{\vec{q}}I_{n,l,n',l'}(\vec{q})$ is the Electron – AP interaction coefficient; $\left|C_{\vec{q}}\right|^{2}=\frac{\hbar q\xi^{2}}{2\rho\upsilon_{s}V}$ ($\vec{q}$ is the phonon wave vector ; υ_s,ξ,ρ,V are the sound velocity, the acoustic deformation potential, the mass density and the normalization volume of specimen, respectively). $\vec{A}(t)=\frac{1}{\Omega}E_{o}\cos(\Omega t)$ is the potential vector, depending on the external field. $I_{n,l,n',l'}(\vec{q})$ is the electron form factor different from that in RQW [8] and in quantum wells [3].

$$I_{n,l,n',l'}(q_{\perp})=\frac{2}{R^{2}}\int_{0}^{R}J_{|n-n'|}(q_{\perp}R)\psi^{*}_{n',l'}(r)\psi_{n,l}(q_{\perp}R)\,rdr \quad (2)$$

In which $\psi_{n,l}(r)$ is radial wave function: $\psi_{n,l}(r)=\frac{1}{J_{(n+1)}(A_{n,l})}J_{n}(A_{n,l}\frac{r}{R})$ (3)

Where the radial wave function containing $A_{n,l}$ is the root of the Bessel function ($J_n(x)$).

$\varphi(\vec{q})$ is the potential undirected: $\varphi(\vec{q})=(2\pi i)^{3}(e\vec{E}+\omega_{c}[\vec{q},\vec{h}])\frac{\partial}{\partial q}\delta(\vec{q})$ (4)

Wave function of confined electron: $\psi_{n,l,\vec{k}}(r,\phi,z)=\begin{cases}0 & \text{khi r>R}\\ \frac{1}{\sqrt{V_{o}}}e^{im\phi}e^{ikz}\psi_{n,l}(r) & \text{khi r<R}\end{cases}$ (5)

Energy Spectrum of confined electron: $\varepsilon_{n,l}(k)=\frac{\hbar^{2}k_{x}^{2}}{2m}+\frac{\pi^{2}\hbar^{2}}{2m}\left(\frac{n^{2}}{L_{x}^{2}}+\frac{l^{2}}{L_{y}^{2}}\right)+\omega_{c}(N+\frac{1}{2})-\frac{1}{2m}\left(\frac{eE_{1}}{\omega_{c}}\right)^{2}$ (6)

Here, $\omega_c=eB/m$ is the cyclotron frequency, R is the radius of wire

From Hamiltonian for Electron–AP interacting system in a CQW with Infinitely High Potential and the procedures as in the previous work [3, 4, 8], we obtain quantum kinetic equations for Electron:

$$i\frac{\partial n_{\gamma,\vec{k}}}{\partial t}=\left\langle\left[a^{+}_{\gamma,\vec{k}}a_{\gamma,\vec{k}},H\right]\right\rangle_{t} \quad (7)$$

Where $n_{\gamma,k}=\left\langle a^{+}_{\gamma,\vec{k}}a_{\gamma,\vec{k}}\right\rangle_{t}$ is the non-equilibrium electron distribution function.

From non-equilibrium electron distribution function:

$$\overline{n}_{\gamma,\vec{k}} \equiv n^{o}_{\gamma,\vec{k}} - \vec{k}\vec{\chi}(\varepsilon_{\gamma,\vec{k}})\frac{\partial n^{(o)}_{\gamma,\vec{k}}}{\partial \varepsilon_{\gamma,\vec{k}}};\quad n^{o}_{\gamma,\vec{k}} = e^{\beta(\varepsilon_F - \varepsilon_{\gamma,\vec{k}})}, \beta = \frac{1}{k_B T}.$$

From quantum kinetic equations, after several operator calculations, we have the link between the current density j_i and the Hall conductivity tensor σ_{ij}. The HC and the component ρ_{xx} of resistance (the MR) are determined by Hall conductivity tensor. Therefore, we obtain the HC and the MR:

$$R_H = \frac{1}{B}\frac{\frac{\omega_c\tau}{1+\omega_c^2\tau^2}\left[\frac{ea}{\omega_c}+\frac{b}{m}\frac{\tau^2}{1+\omega_c^2\tau^2}\right]}{\left\{\frac{-\omega_c\tau}{1+\omega_c^2\tau^2}\left[\frac{ea}{\omega_c}+\frac{b}{m}\frac{\tau^2}{1+\omega_c^2\tau^2}\right]\right\}^2+\left\{\frac{\tau}{1+\omega_c^2\tau^2}\left[ea+\frac{b}{m}\frac{\tau}{1+\omega_c^2\tau^2}(1-\omega_c^2\tau^2)\right]\right\}^2} \tag{8}$$

$$\rho_{xx} = \frac{\frac{\tau}{1+\omega_c^2\tau^2}\left[ea+\frac{b}{m}\frac{\tau}{1+\omega_c^2\tau^2}(1-\omega_c^2\tau^2)\right]}{\left\{\frac{-\omega_c\tau}{1+\omega_c^2\tau^2}\left[\frac{ea}{\omega_c}+\frac{b}{m}\frac{\tau^2}{1+\omega_c^2\tau^2}\right]\right\}^2+\left\{\frac{\tau}{1+\omega_c^2\tau^2}\left[ea+\frac{b}{m}\frac{\tau}{1+\omega_c^2\tau^2}(1-\omega_c^2\tau^2)\right]\right\}^2} \tag{9}$$

In which: the quantities in the equation (8), (9) vary from those in RQW [8]. Therefore, the expression for the HC in RQW is different from that in RQW or 2D. In these expressions, $\vec{h} = \vec{B}/B$ is the unit vector along the magnetic field, $n_{\gamma,\vec{k}}(\mathrm{N}_{\vec{q}})$ is the time independent component of the distribution function of electrons (phonons), γ and γ' are the quantum numbers $(\mathrm{n,l})$ and $(\mathrm{n',l'})$ of electron. $(N,\mathrm{N'})$ are the Landau level $(N = 0,1,2...)$.

Where: $a = \frac{L}{2\pi}\frac{e\beta\hbar}{m^2}\frac{\tau}{1+\omega_c^2\tau_o^2}\exp\left\{\beta\left[\varepsilon_F - \hbar\omega_c\left(N+\frac{n}{2}+\frac{l}{2}+\frac{1}{2}\right)+\frac{e^2E_1^2}{2m\omega_c^2}\right]\right\}\left(\frac{2m}{\beta\hbar^2}\right)^{3/2}\frac{\sqrt{\pi}}{2}$

$$b = \frac{2\pi e}{m}\frac{k_B T\xi^2}{2\rho v_s^2 V} I\sum_{\gamma,\gamma'}(S_1+2S_2+2S_3+2S_4+S_5);\quad c = \exp\left\{\beta\left[\varepsilon_F - \omega_c\left(N+\frac{n}{2}+\frac{l}{2}+\frac{1}{2}\right)+\frac{1}{2m}\left(\frac{eE_1}{\omega_c}\right)^2\right]\right\}$$

$$S_1 = \frac{\beta LmV}{16\sqrt{2}\pi^4}e^{-\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma)/4}\left[(\varepsilon_{\gamma'}-\varepsilon_\gamma)K_o\left(\frac{\varepsilon_{\gamma'}-\varepsilon_\gamma}{2}\right)+\frac{1}{4m^2(\varepsilon_{\gamma'}-\varepsilon_\gamma)}K_1\left(\frac{\varepsilon_{\gamma'}-\varepsilon_\gamma}{2}\right)\right]c$$

$$S_2 = \frac{\beta Lm^3VE_o(\varepsilon_{\gamma'}-\varepsilon_\gamma)}{16\sqrt{2}\pi^2}e^{-\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma)/4}\left[\sqrt{2}K_1\left(\frac{\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma)}{\sqrt{2}}\right)+\frac{1}{\sqrt{2}}K_2\left(\frac{\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma)}{\sqrt{2}}\right)\right]c$$

$$S_3 = \frac{\beta Lm^3VE_o(\varepsilon_{\gamma'}-\varepsilon_\gamma+\Omega)}{16\sqrt{2}\pi^2}e^{-\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma+\Omega)/4}\left[\sqrt{2}K_1\left(\frac{\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma+\Omega)}{\sqrt{2}}\right)+\frac{1}{\sqrt{2}}K_2\left(\frac{\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma+\Omega)}{\sqrt{2}}\right)\right]c$$

$$S_4 = \frac{\beta Lm^3VE_o(\varepsilon_{\gamma'}-\varepsilon_\gamma-\Omega)}{16\sqrt{2}\pi^2}e^{-\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma+\Omega)/4}\left[\sqrt{2}K_1\left(\frac{\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma-\Omega)}{\sqrt{2}}\right)+\frac{1}{\sqrt{2}}K_2\left(\frac{\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma-\Omega)}{\sqrt{2}}\right)\right]c$$

$$S_5 = \frac{\beta Lm^2V}{32\sqrt{2}\pi^4}e^{-\beta(\varepsilon_{\gamma'}-\varepsilon_\gamma)/4}\left[(\varepsilon_{\gamma'}-\varepsilon_\gamma)K_o\left(\frac{\varepsilon_{\gamma'}-\varepsilon_\gamma}{\sqrt{2}}\right)+\frac{1}{2m}K_1\left(\frac{\varepsilon_{\gamma'}-\varepsilon_\gamma}{\sqrt{2}}\right)\right]c$$

$\beta = 1/(\mathrm{k}_B\mathrm{T}); \mathrm{I} = \int_{-\infty}^{+\infty}\left|I_{\gamma,\gamma'}(\vec{\mathrm{q}})\right|^2 d\vec{q}$;

ε_F is the Fermi level. τ is the momentum relaxation time; $I_{\gamma,\gamma'}(\vec{\mathrm{q}})$ is the electron form factor; k_B is Boltzmann constant; T is temperature. $K_i(\mathrm{x})$ are modified Bessel functions.

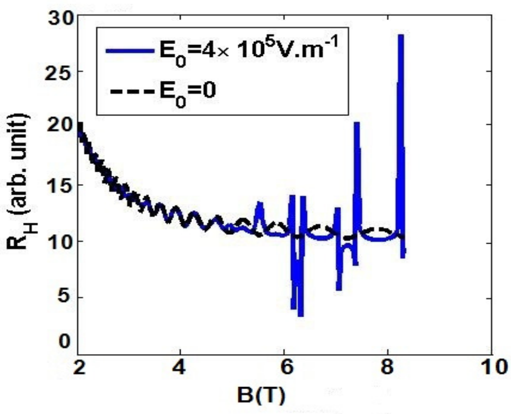
Equations (7) and (8) show the dependency of the MR and the HC on the external field, including the EMW. It is obtained for arbitrary values of the indices $n,n',l,l',\mathrm{N},\mathrm{N}'$. However, it contains the term $I_{\gamma,\gamma'}(\vec{q})$ for which it is difficult to produce an exact analytical result due to the presence of the Hermite polynomials. We will numerically evaluate this term using the computational method. Furthermore, it is seem that the change wires have modified the wave function and energy spectrum of electrons and, consequently, the obtained results are now very different from our previous results in quantum wells, bulk semiconductors and RQW. This differs from one observed in quantum wells (see Ref [3]), whose HC is only dependent on N,N'. The HC in RQW is not only dependent on $n,n',l,l',\mathrm{N},\mathrm{N}'$, which is the same as in CQW, but also L_x,L_y (the sire of RQW). In the next section, we will give a deeper insight into these results by carrying out a numerical evaluation and a graphic consideration using the computational method. The obtained results are very different in comparison to Quantum wells, RQW and 1DEG without EMW.

3. Numerical results and discussions

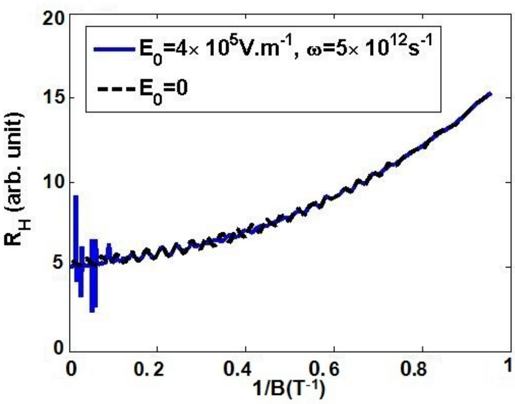
In this section, we present detailed numerical calculations about the dependence of the HC and MR on the frequency of EMW, the MF of the CQW GaAs/GaAsAl. When the temperature changes with parameters [7]:

$\varepsilon = 12.5, m = 6.006\times10^{-24}, \varepsilon_F = 50meV, \hbar\omega_0 = 36.25meV, \Omega = 3\times10^{13}s^{-1}, k_B = 1.38\times10^{-23}kg/m^3$

$N - N' = 1, n = 1, n' = 0 \div 1, l = 1, l' = 0 \div 1, \tau = 10^{-12}s, \rho = 5320kgm^{-3}, q = 2\times10^5 m^{-1}, \upsilon_s = 5220m/s, \xi = 2.2\times10^{-18}J$



a)

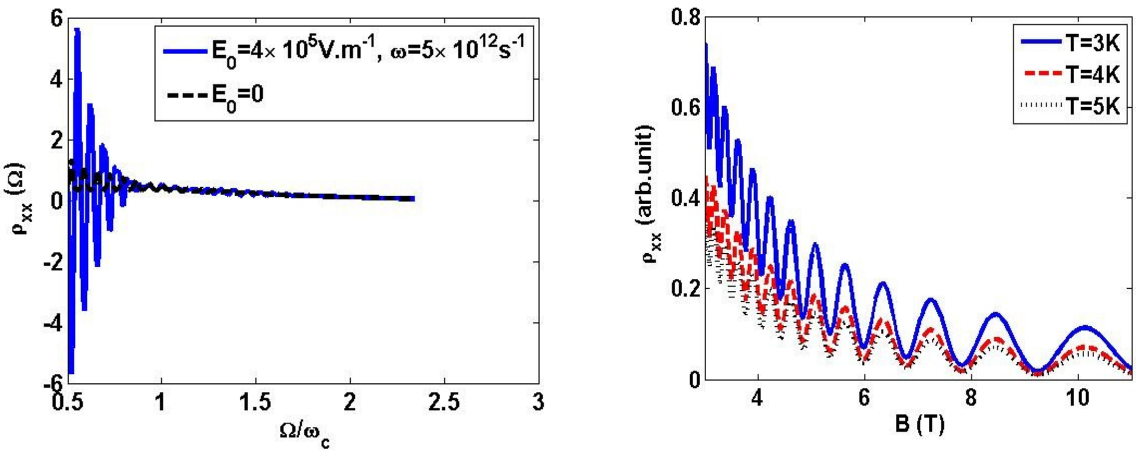


b)

Figure 1. The dependence of the Hall coefficient on a) $B(T)$; b) $1/B(T^{-1})$

The HC is plotted in Fig. 1 as a function of the B and $1/B$ for two cases: presence of the EMW (solid curve) and absence of the EMW (dashed curve). Here $E_1 = 10^2V/m, T = 1K$. We can see clearly the appearance of the typical SdH oscillations with the period is in 1/B. We saw that the conductance of a 2DEG oscillates in a MF and is periodic $1/B$ where B is the flux density. We know that in order for these oscillations to be manifested, the electrons must be able to complete cyclotron orbits and that can happen only if the diameter of smallest orbit $2r_c$ is smaller than the effective width of the quantum wire, which is given $2\sqrt{\hbar/(m^*\omega_o)}$ by [6]. Therefore, SbH oscillations in QW will appear when the magnetic flux density.

The oscillations in Fig. 1 have been studied in detail both theoretically and experimentally in Ref. [5-7] in case absence of the EMW. As we see from the graphs 1a and 1b, in the case of the absence of EMW, the curves are identical to those in Refs experimentally [5-7]. The amplitude of HC with the presence of HC EMW, however, is higher than that without EMW. In addition, the HC increases when the magnetic field goes up. This is the novel point of HC, which is totally different from that in Refs [5-7]. Like the two-dimensional systems, if the Electron-AP interaction occurs at the low temperature, the SbH oscillations will appear. Nevertheless, the HC values in a CQW are smaller than those in quantum wells [3, 4] and the curves are different from those in quantum wells, 2DEG and bulk semiconductors.



a) b)

Figure 2. The dependence of the MR on a) The Ω/ω_c ; b) The *MF*.

Figure 2a shows the dependence of the MR on the ratio Ω/ω_c for two case presence of the EMW (solid curve) and absence of the EMW (dashed curve). It seems that the oscillation amplitude changes evidently in some regions of the MF in the presence of the EMW. There occurs the beat phenomenon. This is different from that in quantum wells [3]. The dependence of The MR on the ratio Ω/ω_c in the Fig. 2 without EMW is similar to that in the Ref. [7].

Figure 2b shows the dependence of the MR on the magnetic field at different values of the temperature. We can see the appearance of the typical SbH oscillations with the period does not depend on the temperature. This property has been observed in 2DEG and in 1DEG without EMW [3-7]. However, our results are different from those (for type of oscillations) in quantum wells [3], and are obtained experimentally in a quantum wire [6]. The MR can be seen to oscillate and decrease according to the MF increase.

4. Conclusion

In this work, we have studied calculation of the HC and Hall Conductivity in CQWs under the Influence of a Laser Radiation caused by Electron - AP interaction subjected to a crossed dc electric and MFs. The Electron–AP interaction is taken into account. We obtain the expressions of Hall conductivity as well as HC. The analytical results are numerically evaluated and plotted for a specific quantum wires GaAs/AlGaAs to show clearly the dependence of MR on the MF at different values of the temperature and the ratio Ω / ω_c , when MF is large, the MR can be seen to oscillate and decrease. This confirms that the MR is quite sensitive to the change in the temperature. The decrease of the amplitude of the SdH oscillations in certain intervals of magnetic fields and EMW frequencies is observed in the case of a presence of the high-frequency EMW. The agreement is found between our calculation and some theoretical as well as experimental works for the MR. The HC is plotted in CQW, whose values and the curves are different from those in quantum wells, 2DEG and bulk semiconductors.

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