Calculating the Current Density of the Radio Electrical Effect in Parabolic Quantum Wells

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Abstract— We study the current density of charge carries of the radio electrical effect in parabolic quantum wells (PQW) subjected to a dc electric field $\vec{E}_0$ and in a linearly polarized electromagnetic wave (EMW) ($\vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t}), \vec{H}(t) = [\vec{n}, \vec{E}(t)]$), ($\hbar\omega \ll \bar{\varepsilon}$; $\bar{\varepsilon}$ is an average carrier energy, in this paper), in the presence of a laser radiation $\vec{F}(t) = \vec{F}\sin\Omega t$; $\Omega\tau \gg 1$ (τ is the characteristic relaxation time). By using the quantum kinetic equation method for electrons interacting with acoustic phonon at low temperatures, we obtain the expressions for the drag of the charge carriers in case the electron gas is completely degenerate. The dependence of the current density on the intensity F and the frequency Ω of the laser radiation, the frequency ω of the linearly polarized EMW, the frequency ω_0 of the parabolic potential are obtained. The analytic expressions are numerically evaluated and plotted for a specific quantum wells, GaAs/AlGaAs, to show clearly the dependence of the current density of charge carriers on the radioelectrical effect on above parameters. The results of current density calculation in this case are compared with bulk semiconductors to show the dissimilarity.

1. INTRODUCTION

It is well-known that the confinement of electrons in low-dimensional systems makes their optical and electrical properties considerably different in comparison to bulk materials [1–4]. Thus, there has been considerable interest in the behavior of low-dimensional systems, in particular two-dimensional systems, such as semiconductor superlattices, doped superlattices and quantum wells. In recent years, many papers have dealt with problems related to the incidence of EMW in low-dimensional semiconductor systems. For example, the linear absorption of a weak EMW caused by confined electrons in low dimensional systems has been investigated by using Kubo-Mori method [5, 6]; calculations of the nonlinear absorption coefficients of a strong EMW by using the quantum kinetic equation for electrons [7, 8] have also been reported; or the study of influence of a weak EMW on low-dimensional systems in the presence of a strong EMW has been researched [9–11]. However, research into influence of two EMW in PQW is still open.

The radioelectrical effect (RE) which is explained by the momentum transfer from photons to the electron, can be understood quasi-classically as being the result of the action of the Lorentz force on charge carriers moving in the ac electric and magnetic fields of the wave [12, 13]. The RE in semiconductors [14–16] have also been investigated and resulted from using the quantum kinetic equation for electrons system. In the past few years, the RE in semiconductor superlattices has been examined under the action of strong electric fields [17, 18] and of an elliptically polarized EMW [19]. The difference between the RE in bulk semiconductors and low-dimensional systems lies in a nonlinear dependence of the current density of charge carriers (CDCC) on EMW [19–23].

In this work, we investigated the CDCC in a PQW under the action of a linearly polarized EMW field $\vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t})$ and in the presence of a laser radiation field $\vec{F}(t) = \vec{F}\sin\Omega t$. We consider the case in which the electron-acoustic phonon interaction at low temperatures is assumed to be dominant and electron gas to be completely degenerate. Numerical calculations are carried out with a specific GaAs/GaAsAl quantum wells. The comparison of the result of quantum wells to bulk semiconductors shows that difference.

2. CALCULATING THE CURRENT DENSITY OF THE RADIO ELECTRICAL EFFECT IN PQW

2.1. Quantum Kinetic Equation for Electrons in PQW

We examine the motion of an electron in PQW confined to the parabolic potential $V(z) = m\omega_0^2 z^2/2$ and that its energy spectrum is quantized into discrete levels. We assume that the quantization direction is the z direction. In this wok, we consider the system (the CDCC and scatterers), which is placed in a linearly polarized EMW field ($\vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t})$, $\vec{H}(t) = [\vec{n}, \vec{E}(t)]$), ($\hbar\omega \ll \bar{\varepsilon}$; $\bar{\varepsilon}$

is an average carrier energy), in a dc electric field $\vec{E}_0$ and in the presence of a laser radiation field $\vec{F}(t) = \vec{F}\sin\Omega t$.

The Hamiltonian of the electron-acoustic phonon system in the PQW in the second quantization representation can be written as:

$$H = \sum_{N,\vec{p}_\perp} \varepsilon_N\left(\vec{p}_\perp - \frac{e}{\hbar c}\vec{A}(t)\right)\cdot a^+_{N,\vec{p}_\perp} a_{N,\vec{p}_\perp} + \sum_{\vec{q}} \hbar\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}} + \sum_{\substack{N,N'\\ \vec{p}_\perp,\vec{q}}} D_{N,N'}(\vec{q}).a^+_{N',\vec{p}_\perp+\vec{q}_\perp} a_{N,\vec{p}_\perp}\left(b_{\vec{q}} + b^+_{-\vec{q}}\right) \quad (1)$$

where N denotes the quantization of the energy spectrum in the z direction ($N = 1, 2, \ldots$), $|N, \vec{p}_\perp\rangle$ and $|N', \vec{p}_\perp + \vec{q}_\perp\rangle$ are electron states before and after scattering, $a^+_{N,\vec{p}_\perp}$ and $a_{N,\vec{p}_\perp}$ ($b^+_{\vec{q}}$ and $b_{\vec{q}}$) are the creation and annihilation operators of electron (phonon); $\omega_{\vec{q}}$ is the frequency of a phonon with the wave vector $\vec{q} = (\vec{q}_\perp, q_z)$; $\vec{A}(t)$ is the vector potential of laser field; $D_{N,N'}(\vec{q}) = C_{\vec{q}} I_{N,N'}(q_z)$, where $I_{N,N'}(q_z)$ is the electron form factor in the PQW, $C_{\vec{q}}$ is the electron-acoustic phonon interaction constant: $\left|C_{\vec{q}}\right|^2 = \frac{\xi^2\cdot q}{2\rho v_S V} = C_0 q$, here V, ρ, v_S and ξ are the volume, the density, the acoustic velocity and the deformation potential constant, respectively.

The electron energy takes the simple:

$$\varepsilon_N(\vec{p}_\perp) = \hbar\omega_p\left(N + \frac{1}{2}\right) + \frac{\hbar^2\vec{p}_\perp^2}{2m} \quad (N = 0, 1, 2, \ldots) \quad (2)$$

with $\omega_p^2 = \omega_0^2 + \omega_H^2$ and $\omega_H = eH/mc$ as the confinement and the cyclotron frequencies. The quantum kinetic equation for electrons in the constant scattering time (τ) approximation takes the form [17–19]

$$\frac{\partial f_{N,\vec{p}_\perp}(t)}{\partial t} - \left(e\vec{E}(t) + e\vec{E}_0 + \omega_H\left[\vec{p}_\perp, \vec{h}\right]\right)\frac{\partial f_{N,\vec{p}_\perp}(t)}{\partial \vec{p}_\perp} + \frac{\vec{p}_\perp}{m}\frac{\partial f_{N,\vec{p}_\perp}(t)}{\partial \vec{r}} = -\frac{f_{N,\vec{p}_\perp}(t) - f_0(\varepsilon_{N,\vec{p}_\perp})}{\tau} \quad (3)$$

where $\vec{h} = \frac{\vec{H}(t)}{H(t)}$ is the unit vector in the direction of magnetic field; $f_0(\varepsilon_{N,\vec{p}_\perp})$ is the equilibrium electron distribution function (Fermi-Dirac distribution); $f_{N,\vec{p}_\perp}(t)$ is an unknown electron distribution function perturbed due to the external fields.

In order to find $f_{N,\vec{p}_\perp}(t) = \langle a^+_{N,\vec{p}_\perp} a_{N,\vec{p}_\perp}\rangle_t$, we use the general quantum equation for the particle number operator or the electron distribution function

$$i\hbar\frac{\partial}{\partial t} f_{N,\vec{p}_\perp}(t) = \left\langle\left[a^+_{N,\vec{p}_\perp} a_{N,\vec{p}_\perp}, H\right]\right\rangle_t \quad (4)$$

From Eqs. (3) and (4), using the Hamiltonian in Eq. (1), we obtain the quantum kinetic equation for electrons in PQW

$$\begin{aligned}
&-\left(e\vec{E}(t) + e\vec{E}_0 + \omega_H\left[\vec{p}_\perp, \vec{h}(t)\right]\right)\frac{\partial f_{N,\vec{p}_\perp}(t)}{\partial \vec{p}_\perp} \\
=& -\frac{f_{N,\vec{p}_\perp}(t) - f_0(\varepsilon_{N,\vec{p}_\perp})}{\tau} + \frac{2\pi}{\hbar}\sum_{N',\vec{q}} |D_{N,N'}(\vec{q})|^2 \sum_{l=-\infty}^{+\infty} J_l^2(\vec{a}\vec{q}_\perp) \\
&\times\left\{\left[f_{N',\vec{p}_\perp+\vec{q}_\perp}(t).(N_{\vec{q}}+1) - f_{N,\vec{p}_\perp}(t)\cdot N_{\vec{q}}\right]\times\delta\left(\varepsilon_{N',\vec{p}_\perp+\vec{q}_\perp} - \varepsilon_{N,\vec{p}_\perp} - \hbar\omega_{\vec{q}} - l\hbar\Omega\right)\right. \\
&\left.+\left[f_{N',\vec{p}_\perp-\vec{q}_\perp}(t).N_{\vec{q}} - f_{N,\vec{p}_\perp}(t)\cdot(N_{\vec{q}}+1)\right]\times\delta\left(\varepsilon_{N',\vec{p}_\perp-\vec{q}_\perp} - \varepsilon_{N,\vec{p}_\perp} + \hbar\omega_{\vec{q}} - l\hbar\Omega\right)\right\} \quad (5)
\end{aligned}$$

where $J_l(x)$ is the Bessel function of argument x; $\vec{a} = \frac{e\vec{F}}{m\Omega^2}$; $N_{\vec{q}} + 1 \approx N_{\vec{q}} = \frac{1}{\exp\{\beta\hbar v_S q_\perp\}-1}$ is the time-independent component of distribution function of phonons, here $\beta = \frac{1}{k_B T}$.

2.2. Calculating the CDCC of the RE in PQW

For simplicity, we limit the problem to the case of $l = 0, \pm 1$. We multiply both sides of Eq. (5) by $(-e/m)\vec{p}_\perp\cdot\delta(\varepsilon - \varepsilon_{N,\vec{p}_\perp})$ and carry out the summation over N and $\vec{p}_\perp$. We obtain

$$\frac{\vec{R}_0(\varepsilon)}{\tau} = \vec{Q}_0(\varepsilon) + \vec{S}_0(\varepsilon) + \omega_H\left[\vec{R}(\varepsilon) + \vec{R}^*(\varepsilon), \vec{h}\right] \quad (6)$$

The total current density is given by

$$\vec{j}_{tot} = \vec{j}_0 + \vec{j}_1(t) = \int_0^\infty \left\{ \vec{R}_0(\varepsilon) + \left[\vec{R}(\varepsilon) \cdot e^{-i\omega t} + \vec{R}^*(\varepsilon) \cdot e^{i\omega t} \right] \right\} d\varepsilon \tag{7}$$

In the case, $\omega_{\vec{q}} \ll \Omega$ ($\omega_{\vec{q}}$ is the frequency of acoustic phonons), so we let it pass. After some mathematical manipulation Eq. (7), we obtain the expression for the CDCC of the RE in PQW for the case electron-acoustic phonon scattering:

$$\begin{aligned} j_i = (j_0)_i + (j_1)_i = & \tau(\varepsilon_F)\delta_{ik} \cdot \delta_{kn}\left(a_0 - \frac{e}{m}\tau(\varepsilon_F)b_0\right)\frac{E_{0n}}{2} + \frac{\omega_p\tau^2(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\varepsilon_{ikl}h_l\delta_{kn}\left(a_0 - \frac{e}{2m}\tau(\varepsilon_F)b_0\right)\frac{E_n}{2} \\ & + \frac{\tau(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\delta_{ik}\delta_{km}\left(a_0 - \frac{e}{2m}\frac{1-\omega^2\tau^2(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\tau(\varepsilon_F)b_0\right)\frac{E_m}{2} \end{aligned} \tag{8}$$

where δ_{ik} is the Kronecker delta; ε_{ikl} being the antisymmetrical Levi-Civita tensor, and

$$\begin{aligned} a_0 &= \frac{e^2 L_x}{\pi}\sum_N a_N = \frac{e^2 L_x}{\pi}\sum_N \sqrt{\frac{2}{m\hbar^2}\left(\varepsilon_F - \hbar\omega_p\left(N + \frac{1}{2}\right)\right)}; \\ b_0 &= \frac{8\pi e \cdot C_0 L_x}{(2\pi\hbar)^3}(b_1 + b_2 + b_3 - b_4 - b_5 - b_6); \\ b_1 &= -\sum_{N,N'}\frac{I_{N,N'}}{\sqrt{\Delta_1}}\left\{\frac{(q_1^+)^3}{e^{\hbar\beta \mathrm{v}_S(q_1^+)} - 1} \times \left[1 - \frac{e^2F^2(q_1^+)^2}{4m^2\Omega^4}\right] + \frac{(q_1^-)^3}{e^{\hbar\beta \mathrm{v}_S(q_1^-)} - 1} \times \left[1 - \frac{e^2F^2(q_1^-)^2}{4m^2\Omega^4}\right]\right\} \\ b_2 &= -\sum_{N,N'}\frac{I_{N,N'}}{\sqrt{\Delta_2}}\frac{e^2F^2}{8m^2\Omega^4}\left\{\frac{(q_2^+)^5}{e^{\hbar\beta \mathrm{v}_S(q_2^+)} - 1} + \frac{(q_2^-)^5}{e^{\hbar\beta \mathrm{v}_S(q_2^-)} - 1}\right\} \\ b_3 &= b_2(\Delta_2 \to \Delta_3); \quad b_4 = b_1(q_1 \to q_4); \quad b_5 = b_2(q_2 \to q_5); \quad b_6 = b_3(q_2 \to q_6); \\ \sqrt{\Delta_1} &= \hbar^2 a'_N; \quad q_1^\pm = -m(a_N \mp a'_N); \quad \sqrt{\Delta_2} = \hbar^2\sqrt{a'^2_N - \frac{2\Omega}{m\hbar}}; \quad q_2^\pm = -ma_N \pm \frac{m}{\hbar^2}\sqrt{\Delta_2}; \\ \sqrt{\Delta_3} &= \hbar^2\sqrt{a'^2_N + \frac{2\Omega}{m\hbar}}; \quad q_4^\pm = m(a_N \pm a'_N); \quad q_5^\pm = ma_N \pm \frac{m}{\hbar^2}\sqrt{\Delta_2}; \quad q_6^\pm = ma_N \pm \frac{m}{\hbar^2}\sqrt{\Delta_3} \end{aligned}$$

with ε_F is the Fermi level; L_x is the normalization length in the x-direction.

Choose the axis Oz along $\vec{n}$, $\vec{Ox} \uparrow\uparrow \vec{E}$, and $\vec{Oy} \uparrow\uparrow \vec{H}$, from Eq. (8), we find the CDCC components

$$j_x = \tau(\varepsilon_F)\left(a_0 - \frac{e}{m}\tau(\varepsilon_F)b_0\right)\frac{E_{0x}}{2} + \frac{\tau(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\left(a_0 - \frac{e}{2m}\frac{1-\omega^2\tau^2(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\tau(\varepsilon_F)b_0\right)\frac{E_x}{2} \tag{9}$$

$$j_y = \tau(\varepsilon_F)\left(a_0 - \frac{e}{m}\tau(\varepsilon_F)b_0\right)\frac{E_{0y}}{2} \tag{10}$$

$$j_z = \tau(\varepsilon_F)\left(a_0 - \frac{e}{m}\tau(\varepsilon_F)b_0\right)\frac{E_{0z}}{2} + \frac{\omega_p\tau^2(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\left(a_0 - \frac{e}{2m}\tau(\varepsilon_F)b_0\right)\frac{h_yE_x}{2} \tag{11}$$

Equations (9), (10) and (11) show the dependence of the CDCC of the RE in PQW on the intensity F and the frequency Ω of the laser radiation, the frequency ω of the linearly polarized EMW field, the frequency ω_0 of the parabolic potential. As one can see, the above equations clearly show the dependence of the CDCC on the quantum number N, N' of the electron's state which is confined by the parabolic potential $V(z) = m\omega_0^2 z^2/2$. This is different from that in the normal bulk semiconductors [13–16, 22].

3. NUMERICAL RESULTS AND DISCUSSION

In this section, the CDCC of the RE is numerically calculated for the specific case of GaAs/GaAsAl PQW. The parameters used in the calculations are as follows [7, 8]: $\varepsilon_F = 30\,\text{meV}$; $\xi = 13.5\,\text{eV}$;

$\rho = 5.32\,\mathrm{g\cdot cm^{-3}}$, $v_S = 5378\,\mathrm{m\cdot s^{-1}}$, $m = 0.0665\,m_0$ (m_0 is the mass of free electron); $L_x = 10^{-9}\,\mathrm{m}$, and we choose $\tau \sim 10^{-12}\,\mathrm{s}^{-1}$;

In Fig. 1 and Fig. 2, we show the dependence of the CDCC's components $\langle j_x\rangle$ and $\langle j_z\rangle$ on the frequency Ω of the laser radiation at different values of the confinement frequency ω_0. In Fig. 2, we can see that the values of the component $\langle j_z\rangle$ are much larger than $\langle j_x\rangle$. That is due to the quantization on Oz axis of electrons. Moreover, we can describe the behavior of the CDCC in Fig. 1 and Fig. 2 as follows: each curve has one maximun (peak) and one minimun. We know that in PQW, state of the electron is quantized into discrete levels by quantum number N. So when the energy of a photon of laser wave is equal to the difference of two electron energy levels: $\varepsilon_{N',\vec{p}_\perp-\vec{q}_\perp} - \varepsilon_{N,\vec{p}_\perp} \pm \hbar\Omega$, resonance peak will appear.

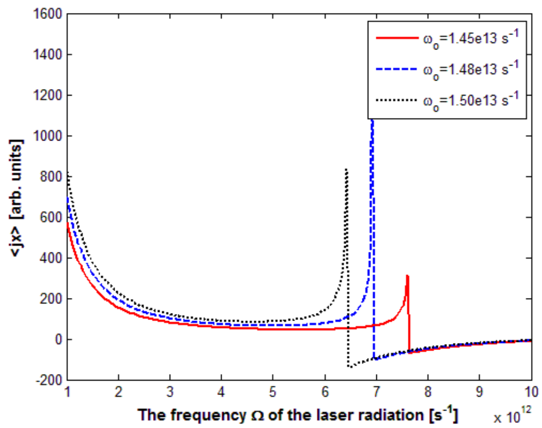

Figure 1: The dependence of $\langle j_x\rangle$ on Ω at $\omega = 5\times10^{12}$ (s^{-1}), $T = 2\,\mathrm{K}$, $E_{0x} = 10^5\,\mathrm{V/m}$ and $F = 10^6\,\mathrm{V/m}$.

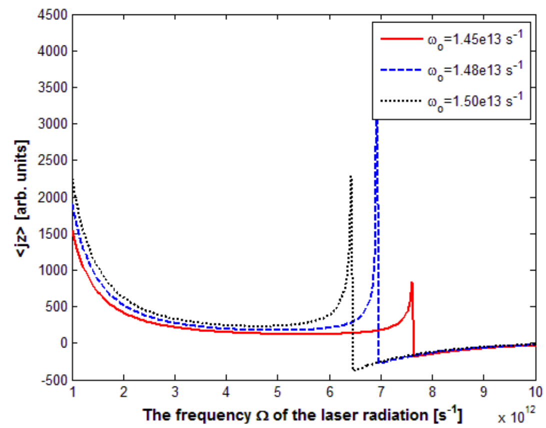

Figure 2: The dependence of $\langle j_z\rangle$ on Ω at $\omega = 5\times10^{12}$ (s^{-1}), $T = 2\,\mathrm{K}$, $E_{0x} = 10^5\,\mathrm{V/m}$ and $F = 10^6\,\mathrm{V/m}$.

The dependence of the CDCC component $\langle j_x\rangle$ on the frequency ω of EMW is described by Fig. 3. In Fig. 3, we can see that $\langle j_x\rangle$ depends strongly and nonlinear on ω. When the frequency ω changes, the curves of $\langle j_x\rangle$ have a maximun value (or a minimun value). All those values correspond to the resonant condition $\hbar\omega_p = \hbar\omega$ or $\hbar\sqrt{\omega_0^2+\omega_H^2} = \hbar\omega$. Besides, Fig. 3 shows that if the frequency Ω of laser radiation slowly changes, ¡jx¿ will quickly change.

In Fig. 4, we show the dependence of the CDCC component $\langle j_z\rangle$ on the frequency ω of EMW. From the figure we can see that the curves can begin at the negative branch or at the positive branch, which depends on the value of the frequency Ω. When the frequency ω of EMW increases,

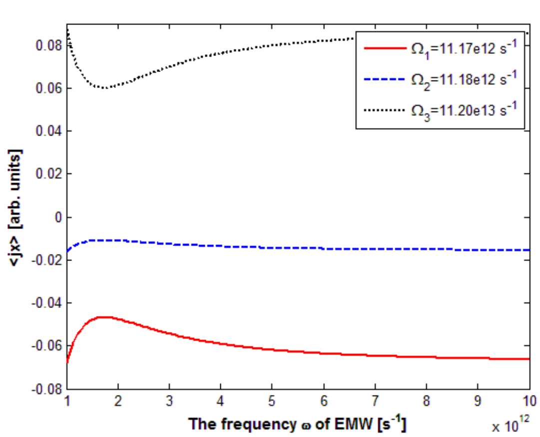

Figure 3: The dependence of $\langle j_x\rangle$ on ω at $\omega_0 = 1.5\times10^{13}$ (s^{-1}), $T = 2\,\mathrm{K}$, $E_{0x} = 10^5\,\mathrm{V/m}$ and $F = 10^6\,\mathrm{V/m}$.

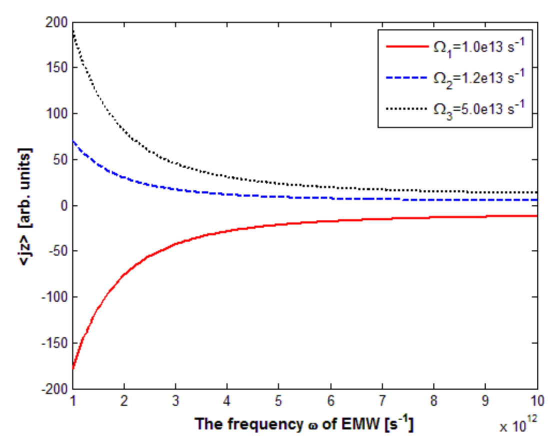

Figure 4: The dependence of $\langle j_z\rangle$ on ω at $\omega_0 = 1.5\times10^{13}$ (s^{-1}), $T = 2\,\mathrm{K}$, $E_{0x} = 10^5\,\mathrm{V/m}$ and $F = 10^6\,\mathrm{V/m}$.

the values of $\langle j_z \rangle$ on these curves are decreasing to zero.

4. CONCLUSIONS

In this paper, we have investigated the CDCC of the RE in PQW subjected to a dc electric field, a linearly polarized EMW field and in the presence of a laser field. The electron — acoustic phonon interaction is taken into account at low temperature and electron gas is completely degenerate. We obtain the expressions for the CDCC of the RE in PQW. We interpret the dependences of the CDCC of the RE on the frequency Ω of the laser radiation field, on the frequency ω of the linearly polarized EMW field, on the frequency ω_0 of the parabolic potential. The analytical results are numerically evaluated and plotted for specific quantum well, GaAs/AlGaAs, to confirm clearly once again that the the CDCC of the RE strongly depends on the above elements. The comparison of the result of quantum well to bulk semiconductors shows that difference.

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