Ultrafast Fiske effect in semiconductor superlattices induced by the coupling of electron Bloch oscillations to longitudinal optical phonons and coherent plasmons

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Abstract. We show that resonant coupling of coherent electron Bloch oscillations to longitudinal optical phonons in a wide-miniband semiconductor superlattice induces a unidirectional transient electron current in the system. This effect has a profound analogy to the DC Fiske effect observed when a superconductor Josephson junction or a superfluid weak link is coupled, respectively, to an electromagnetic or acoustic resonator. In the ultrafast Fiske effect, the coupling opens an elastic rectifying channel which exists only during the coherence time of the electron wave packets involved. In the considered ultrafast coupling effect, the longitudinal optical phonons in the superlattice play the role of the resonator coupled to the free damped electron Bloch oscillations, via both their amplitude and phase. We also show that similar unidirectional transient current, but with the opposite sign, is induced by non-resonant coupling of electron Bloch oscillations to coherent electron plasma oscillations. This unidirectional transient current can probably explain the origin, the sign and the carrier-density dependence of the self-induced coherent unidirectional current, which was observed in an undoped biased semiconductor superlattice with photo-excited carriers.

1. Introduction
A fundamental property of a quasiparticle in a periodic potential subject to an external force is its localization by Bragg reflection which leads to temporal and spatial oscillations known as Bloch oscillations [1]. They were first observed as oscillations of electron wave packets in semiconductor superlattices (SSLs) [2-7], and later as a periodic motion of ensembles of ultracold atoms [8,9] and Bose-Einstein condensates [10,11] in tilted optical lattices.

It has been known for a long time that the dynamics of Bloch-oscillating electron wave packets in SSLs is profoundly analogous to the dynamics of Cooper pairs in superconductor Josephson junctions [12,13]. The oscillations are in all cases a consequence of a time-dependent phase difference of the wavefunctions involved. Several of the effects originating from the tunneling nature of the current in Josephson junctions have found their counterparts in corresponding electron wave-packet dynamics in SSLs. The Bloch oscillations in an electrically biased superlattice correspond to the AC Josephson effect, while the inverse Bloch effect [14] refers to the appearance of the Shapiro-like resonances in the high-field DC current upon illumination of the device with THz electromagnetic radiation.
Recently, a new effect was identified in SSL which finds its analog in supercurrent systems. When a superlattice is subjected to a magnetic field, tilted to the electric bias field, the Bloch oscillations couple to the in-plane cyclotron oscillations which then leads to a DC current \cite{15,16}. It exists only while the two oscillations retain their coherence. An equivalent DC current, termed Fiske current, is observed when superconductor Josephson junction is coupled to an electromagnetic resonator \cite{17,18}, or when a superfluid weak link is coupled to an acoustic resonator \cite{19,20}. One finds a resonantly enhanced DC charge or mass supercurrent occurring upon resonance between the Josephson frequency and the eigenfrequency of the coupled resonator. In the ultrafast Fiske effect, the coupling opens an elastic rectifying channel which only exists during the coherence time of the photo-excited electron wave packets involved. The ultrafast Fiske effect is intimately related with the coherent (phase-dependent) nature of the transient electron Bloch oscillations, which exponentially decay in time (from the excitation instant) due to dephasing (decoherence) of the photo-excited electron wave packets.

2. Discussion

In this work we show that resonant coupling between coherent electron Bloch oscillations and longitudinal optical phonons in a wide-miniband SSL induces a transient unidirectional (quasi-DC) electron current in the system. In the considered coupling effect, the longitudinal optical phonons in the superlattice play the role of the resonator coupled to the free damped electron Bloch oscillations, via both their amplitude and phase. We also show that similar unidirectional transient current, but with the opposite sign, is caused by non-resonant coupling between the electron Bloch oscillations and coherent electron plasma oscillations. This transient coherent current can probably explain the origin, the sign and its change by the excitation conditions, and the quadratic carrier-density dependence of the coherent self-induced quasi-DC current, which was observed in a biased SSL with photo-excited carriers \cite{21}.

In order to theoretically address these phenomena, we work in the semiclassical picture which is known to adequately describe quantum coherence phenomena because a macroscopically large number of carriers contributes to the coherent response \cite{13}. We consider the coupling of the electron velocity \(V_z\) along the axis of a biased polar (GaAs/AlGaAs) semiconductor superlattice to the relative (anion-cation) longitudinal ionic displacement \(w_z\). With this we take into account that optically excited heavy holes do not perform Bloch oscillations because of Stark localization of heavy carriers in a biased superlattice and remain at the point of excitation during the relevant time scale \cite{15,16}. If we assume that coherent carriers were photo-excited in the superlattice at \(t = 0\), then the electron velocity \(V_z\) for \(t > 0\) will be given by \(V_z = v_{z,\text{max}}^* \exp(-\gamma t) \sin(p_zd/\hbar)\) \cite{15,16}. Here, \(v_{z,\text{max}}^* = \hbar/(|m_z|d)\) is the maximal miniband group velocity, \(m_z\) is effective mass at the bottom \((m_z=0.115 m_e\), see Ref. \cite{22}) or at the top, see below, of the tight-binding electron miniband; \(d\) denotes the superlattice period, \(p_z\) the Bloch momentum along the axis of SSL, and \(\gamma\) the relaxation (dephasing) rate of the Bloch oscillations. The interaction between \(V_z\) and \(w_z\) occurs via both phase (given by \(p_zd/\hbar\) in the expression for \(V_z\)) and amplitude of the electron Bloch oscillations:

\[
\dot{p}_z = eE_z, \tag{1}
\]

\[
E_z = E_{z0} - \frac{4\pi e^* N_z}{\epsilon_\infty} w_z - \frac{4\pi e N_{coh}}{\epsilon_\infty} Z, \quad \dot{Z} = V_z, \tag{2}
\]

\[
\dot{w}_z + 2\gamma_p \dot{w}_z + \omega_{TO}^2 w_z = \frac{e^*}{\mu} E_z. \tag{3}
\]

Here \(E_z\) and \(E_{z0}\) are, respectively, the total and static electric fields; \(\omega_{TO}\) and \(\gamma_p\) are, respectively, the frequency and relaxation rate of the transverse optical phonons; \(\mu\) and \(e^*\) denote, respectively, the anion-cation reduced mass and effective charge; \(N_{coh}\) and \(N_z^*\) are, respectively, the bulk
densities of the photo-excited electrons and anion-cation pairs; $\varepsilon_\infty = 13$ is a background dielectric constant.

We solve Eqs. (1) - (3) with the (bottom-miniband) initial conditions $p_z(0)=0$, $V_z(0)=0$ and $w_z'(0)=0$ ($w'_z$ is a dynamical component of the ionic displacement), which are realized in typical time-resolved experiments with photo-excited carriers in SSLs, see [5,6,7,15,16,22]. In this case Eq. (3) can be written as

$$\ddot{w}_z + 2\gamma_w \dot{w}_z + \omega_{LO}^2 w_z = \frac{e^*}{\mu} \left[ E_{z0} - \frac{4\pi e N_{coh} v_z^{max}}{\varepsilon_\infty \omega_B^{2}} \left[ 1 - \exp(-\gamma t) \cos(\omega_B t - \frac{\gamma}{\omega_B}) \right] \right],$$

where $\omega_B = |eE_{z0}|d/\hbar$ is angular frequency of electron Bloch oscillations which are assumed to be weakly damped, $\omega_B \gg (\gamma, \gamma_p)$; $\omega_{LO}$ is frequency of longitudinal optical oscillations, $\omega_{LO}^2 = \omega_{LO}^2 + 4\pi e^2 N^*_s / (\mu \varepsilon_\infty)$.

From Eqs. (1), (2) and (4) we obtain that the coupling of the Bloch oscillations to the longitudinal optical phonons, given by the second term in r.h.s. of Eq. (2), and to the coherent plasmons, given by the third term in r.h.s. of Eq. (2), results in the following velocity of Bloch-oscillating electrons:

$$V_z = v_z^{max} \exp(-\gamma t) \sin(\omega_B t + \Phi) - \frac{\omega_B \exp(-\gamma t)}{\omega_{LO}} \sin(\omega_{LO} t + \Phi) - (1 - \frac{\omega_B}{\omega_{LO}} \sin \Phi),$$

where

$$C = \frac{4\pi e^2 N_{coh} v_z^{max}}{\varepsilon_\infty \omega_B^2},$$

$$D = \frac{4\pi e^2 N_{coh} 4\pi e^2 N^*_s v_z^{max}}{\varepsilon_\infty \mu \varepsilon_\infty \omega_B^2 \sqrt{(\omega_{LO}^2 - \omega_B^2)^2 + 4\omega_B^2(\gamma - \gamma_p)^2}},$$

$$\Phi = \arccos \left[ \frac{\omega_{LO}^2 - \omega_B^2}{\sqrt{(\omega_{LO}^2 - \omega_B^2)^2 + 4\omega_B^2(\gamma - \gamma_p)^2}} \right].$$

These equations were derived under the assumption of weak non-resonant coupling between Bloch oscillations and coherent plasmons, $\omega_{plz} < \omega_B$, where $\omega_{plz} = 4\pi e^2 N_{coh} / (|m_z| \varepsilon_\infty)$ is electron plasma frequency in the SSL. These equations show that electron Bloch oscillations with the angular frequency $\omega_B$ are accompanied by a transient unidirectional (quasi-DC) drift of the electrons in $z$ direction. This quasi-DC electron velocity is induced by the interference of the resonant and non-resonant contributions (given, respectively, by the terms $\propto D$ and $\propto C$ in r.h.s. of Eq. (5)) with the $\omega_B t$ contribution to the total phase $p_z d/\hbar$ of the electron velocity $V_z$. Resonant contribution is most pronounced when the Bloch oscillations and the longitudinal optical phonons are in resonance, while the non-resonant contribution is caused by the coupling of electron Bloch oscillations to the coherent plasmons. For the resonance case, $\omega_B = \omega_{LO}$, which can be realized in a wide-miniband SSL [23,24], one derives from Eqs. (5)-(8) the following time dependence of the transient unidirectional component of the electron velocity:

$$V_{z,\text{res}}^{d\text{c}}(t) = v_z^{max} \frac{\omega_{plz}^2}{4\omega_B^2} \exp(-\gamma t) \left[ \frac{\omega_{LO}^2 - \omega_{plz}^2}{\gamma - \gamma_p} \left( \exp(-\gamma_p t) - \exp(-\gamma t) \right) - 4\gamma \exp(-\gamma t) \right].$$

In the limit of $\gamma = 0$, finite $\gamma_p$ and $t \gg 1/\gamma_p$, $V_{z,\text{res}}^{d\text{c}}$ transforms into a constant velocity $V_{z,\text{res}}^{dc} = v_z^{max} \frac{\omega_{plz}^2}{4\omega_B^2} \left( \omega_{LO}^2 - \omega_{plz}^2 \right) / (4\gamma_p \omega_B^2)$ and results in a self-induced DC current $J_{z,\text{res}}^{dc} = eN_{coh} V_{z,\text{res}}^{dc}$ fully analogous to that in the Fiske effect in Josephson junctions and superfluid weak links. For the
finite $\gamma$ and $\gamma_p$, $V_{z, res}^{qdc}$ gives rise to the ultrafast transient (quasi-DC) equivalent of the Fiske current.

The quantity measured in the time-domain experiments with photo-excited carriers in SSLs is the time-dependent internal depolarization field $E_{z, dep}^{\text{int}}(t) = -4\pi e N_{\text{coh}} Z(t)/\epsilon_\infty$, since for the longitudinal electromagnetic oscillations one has $\epsilon_\infty E_{z, dep}^{\text{int}} + 4\pi e N_{\text{coh}} V_z = 0$, see Refs. [5,6,7,13,15,16,21]. $Z(t)$ is the time-dependent average electron-hole separation $|Z(t) = \int_0^t V_z(t) dt|$, cf. Eq. (2)], which here is identical to the average (center-of-mass) displacement of electron wave packets. With the use of Eq. (9), we get the following expression for the transient unidirectional depolarization field:

$$E_{z, res}^{\text{dep}}(t) = -\frac{\hbar}{4\pi d} \frac{\omega_{3\text{c}}}{\omega_B} \left[ \frac{\omega_{\text{LO}}^2 - \omega_{\text{TO}}^2}{\gamma - \gamma_p} \left[ 1 - \frac{1 - e^{-(\gamma + \gamma_p)t}}{\gamma + \gamma_p} \right] - \frac{1}{2\gamma} \left( 1 - e^{-2\gamma t} \right) \right].$$  (10)

In typical GaAs/AlGaAs SSLs, the electron Bloch oscillations have higher relaxation rate than the optical phonons, $\gamma \gg \gamma_p$, and one has $\omega_{\text{LO}}^2 - \omega_{\text{TO}}^2 > \gamma^2$ (for $\omega_B \leq \omega_{\text{LO}}$, see Ref. [23]). Therefore the resonant contribution to the quasi-DC depolarization field, given by the first term in r.h.s. of Eq. (10), exceeds the non-resonant one, given by the last term in r.h.s. of Eq. (10). On the other hand, the non-resonant contribution to the quasi-DC depolarization field is finite for $\omega_B \ll \omega_{\text{LO}}$ when the contribution to the depolarization field, caused by the coupling of electron Bloch oscillations to the longitudinal optical phonons, is negligible, see Eqs. (5) - (8). This non-resonant contribution to the depolarization field gives $E_{z, dep}(t) \propto \gamma t$ for $t \ll 1/(2\gamma)$, see Eq. (10). This contribution to the depolarization field can probably explain the origin and the negative sign of the coherent transient quasi-DC current with a quadratic carrier-density dependence, which was observed in Ref. [21] in an undoped biased SSL with carriers, photo-excited at the bottom (lower half) of the electron miniband for $\omega_B \ll \omega_{\text{LO}}$. With Eqs. (9) and (10), this coherent quasi-DC current is equal to $J_{\text{coh, z}}^{qdc} = e N_{\text{coh}} V_{z, res}^{qdc} = -\epsilon_\infty \dot{E}_{z, dep}^{\text{int}}/4\pi \propto -e N_{\text{coh}}$. In the case of the carriers, photo-excited at the top (upper half) of the electron miniband, the carrier charge $e$ in front of the expression (10) for $E_{z, dep}^{\text{int}}(t)$ will change its sign (from negative to positive) due to the change of the type of the photo-excited carriers from electrons to (light) holes caused by the change of the sign of the carrier effective mass $m_z$ (from positive to negative) in the upper half of the electron miniband. This will result in the change of the sign of the self-induced coherent quasi-DC current $J_{\text{coh, z}}^{qdc}$, which is a consequence of the quantum nature of this current. For the photo-generation of the carriers close to the center of the electron miniband (or to the center of the Wannier-Stark ladder), the coherent quasi-DC carrier velocity $V_{z, coh}^{qdc}$ and therefore the coherent self-induced quasi-DC current $J_{\text{coh, z}}^{qdc}$ will go to zero together with $1/m_z^2$, see Eq. (9), because of the divergency of the carrier effective mass $m_z$ close to the center of the miniband, see also Ref. [13]. The change of the sign of the coherent self-induced quasi-DC current for the carriers, photo-excited at the upper half of the miniband, in comparison with that induced by the carriers, photo-excited at the lower half of the miniband, and the disappearance of such current for the carriers, photo-excited close to the center of the miniband, was observed in a biased SSL in [21].

3. Conclusion

In conclusion, we predict the existence of a self-induced transient unidirectional coherent current in an optically excited wide-miniband biased semiconductor superlattice. This current is substantially enhanced at the resonance between the electron Bloch oscillations and the longitudinal optical phonons. The resonance effect has a profound analogy to the Fiske effect in superconductor Josephson junctions and superfluid weak links, and to the ultrafast Fiske effect in semiconductor superlattices in tilted electric and magnetic fields. We also predict the existence of self-induced quasi-DC coherent current, caused by non-resonant coupling of
the electron Bloch oscillations to the coherent plasmons. This quasi-DC current can probably explain the origin, the sign and the quadratic carrier-density dependence of the coherent quasi-DC current, which was observed in an undoped biased semiconductor superlattice with carriers, photo-excited either at the bottom, close to the center or at the top of the electron miniband [21].

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