Weiss oscillations in surface acoustic wave propagation

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The interaction of a surface acoustic wave (SAW) with a two-dimensional electron gas in a periodic electric potential and a classical magnetic field is considered. We calculate the attenuation of the SAW and its velocity change and show that these quantities exhibit Weiss oscillations.

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Oscillations in the dc magnetoresistance, known as Weiss oscillations, can be observed in high mobility two-dimensional electron gas (2DEG) subject to a perpendicular magnetic field \( B \) and a periodic laterally-modulated potential. These oscillations are geometric in nature, occurring whenever the cyclotron radius \( R_c \) is an integral multiple of the modulation period, \( d \).

Surface acoustic waves (SAWs) are known to be a very effective tool to study the properties of a 2DEG. Recently the remarkable effect of a periodic potential on the SAW propagation has been observed in the quantum Hall regime; this problem was addressed theoretically in [1]. In this Letter we focus on a different aspect: the possibility to observe Weiss oscillations in the ac electric field of a SAW in weak (classical) magnetic fields.

We show that when the SAW length is long compared to the grating period and the electron cyclotron radius the grating just renormalizes the conductivity \( \sigma(q, \omega) \), where \( \omega \) and \( q \) are the frequency and the wave vector of the SAW. This means that the propagation of the SAW in the modulated 2DEG can be described as propagation in a uniform 2DEG having an effective conductivity

\[
\sigma_{\text{eff}}(q, \omega) = \sigma(q, \omega) + \delta \sigma(q, \omega),
\]

where the first term is the conductivity of the 2DEG without grating and the second is the renormalization due to the grating. The grating-induced contribution \( \delta \sigma \) will be shown to exhibit Weiss oscillations, as manifested in the SAW absorption and the velocity shift.

Due to the piezoelectric properties of GaAs the deformation wave is followed by an electrical field wave, which in the plane of the 2DEG is \( \mathbf{E}^0(r, t) = \mathbf{E}^0 \exp(-i \omega t + i q r) + \text{c.c.} \). We assume the field to be longitudinal, \( \mathbf{E}^0 \parallel q \), which corresponds to the usual experimental geometry. This field is screened by the 2DEG, and because of the modulation the screened (total) field \( \mathbf{E}(r, t) \) has spatial Fourier components with wave vectors \( q_s = q + sp, (s = 0, \pm 1, \pm 2, \ldots) \), where \( p \) is the wave vector of the grating, \( p = 2\pi/d \). It follows that \( \mathbf{E}(r, t) = \sum_s \mathbf{E}_s \exp(-i \omega t + i q_s r) + \text{c.c.} \). The unscreened field has in these notations only the \( s = 0 \) Fourier component, \( q_0 \equiv q \), and \( \mathbf{E}^0 = \delta_{s,0} \mathbf{E}^0 \). The current density created by the SAW is \( j(r, t) = \sum_s j_s \exp(-i \omega t + i q_s r) + \text{c.c.} \) and we define a matrix of tensorial conductivities \( \sigma_{s,s'} \) by

\[
\mathbf{j}_s = \sum_{s'} \sigma_{s,s'} \mathbf{E}_{s'}.
\]

Since the SAW velocity \( v = \omega / q \) (equal to \( 2.8 \times 10^8 \text{cm/sec in GaAs} \) is much less than the light velocity one can neglect retardation effects and find the screening field solving a quasistatic problem. The result is (a detailed account of our work will be given elsewhere)

\[
\mathbf{E}_s - \mathbf{E}^0_s = -\frac{2\pi i}{\omega \epsilon_0 q_s} \mathbf{q}_s \cdot \sum_{s'} \sigma_{s,s'} \cdot \mathbf{E}_{s'} ,
\]

where \( \epsilon_0 \) is the effective dielectric constant of the background.

It follows from this equation that when \( \mathbf{E}^0 \parallel q \) as assumed, then for all \( s \) one has \( \mathbf{E}_s \parallel q_s \), i.e. the total screened field is also longitudinal. In this case one can put \( \mathbf{E}_s = (q_s / q_s) E_s \) and eliminate the tensorial properties, obtaining from Eq. (1) the relation between the screened and unscreened fields in a scalar form \( \sum_{s'} \epsilon_{s,s'} E'_{s'} = \delta_{s,0} E^0 \), where the longitudinal dielectric constant matrix is \( \epsilon_{s,s'} = \delta_{s,0} + (2\pi i / \omega \epsilon_0) q_s \sigma_{s,s'} \) and the longitudinal conductivity matrix is \( \sigma_{s,s'} = (q_s / q_s) \cdot \sigma_{s,s'} \cdot (q_s / q_s) \).

The absorption \( Q \) of the SAW is given by a spatial and temporal average of \( \mathbf{j} \cdot \mathbf{E} \). Using the field and current representations one finds for longitudinal fields

\[
Q = \sum_{s,s'} E'_s \sigma_{s,s'} E'_{s'} + \text{c.c.}
\]

Expressing the screened field \( \mathbf{E} \) in terms of the SAW field \( \mathbf{E}^0 \) one has

\[
Q / |\mathbf{E}^0|^2 = i \sigma_M (\epsilon^{-1})_{0,0} + \text{c.c.} = -2 \sigma_M \Im(\epsilon^{-1})_{0,0}.
\]

Here \( (\epsilon^{-1})_{0,0} \) is the \( s = 0, s' = 0 \) matrix element of
the matrix inverse to $\epsilon$ and $\sigma_m = \epsilon_c v/2\pi$ (equal to $1 \times 10^{-2}(e^2/h)$ for GaAs).

Furthermore, it can be shown [14] that in the lowest order of the piezoelectric coupling constant $\alpha$ (in GaAs $\alpha^2/2 = 3.2 \times 10^{-4}$) the renormalized dispersion relation of the SAW takes the form

$$\omega = vq\left[1 + (\alpha^2/2)(\epsilon^{-1})_{0,0}\right].$$

As a consequence, both the relative shift of the SAW velocity $\Delta v/v$ and its attenuation coefficient per unit length $\Gamma$ are given in terms of $(\epsilon^{-1})_{0,0}$ as follows

$$\Delta v/v = (\alpha^2/2)\Re(\epsilon^{-1})_{0,0};$$

$$\Gamma = -q(\alpha^2/2)\Im(\epsilon^{-1})_{0,0}. \quad (5)$$

For the calculation of the longitudinal conductivities which define $(\epsilon^{-1})_{0,0}$ we start with the kinetic equation for the distribution function $f(r, k, t)$ of the 2DEG electrons in a form used in [2]

$$\left[\frac{\partial}{\partial t} + v \nabla + \frac{\epsilon}{c} v \times \mathbf{B} \frac{\partial}{\partial \mathbf{k}} + \mathbf{eE}(r, t) - \nabla U(r) \frac{\partial}{\partial \mathbf{k}}\right] f = -(f - \langle f \rangle)/\tau. \quad (6)$$

Here, $v = k/m$, $U(r)$ denotes the modulating potential in the plane of the 2DEG, $\mathbf{E}(r, t)$ is the total electric field of the SAW, $\tau$ is the momentum relaxation time (assuming short range scattering potential), the angular brackets $\langle . . . \rangle$ denote an average over the directions of $\mathbf{k}$, and $\epsilon = -|\epsilon|$ is the electron charge.

When $\mathbf{E}(r, t) = 0$ the 2DEG is in equilibrium and the solution of Eq. (6) is $f_0(r, k) = f_T(\varepsilon_k + U(r))$, where $\varepsilon_k = k^2/2m$ and $f_T(\varepsilon)$ is the Fermi distribution. To linearize Eq. (6) with respect to $\mathbf{E} = \mathbf{E}(r) \exp(-i\omega t) + c.c.$ we write $f(r, k, t) = f_0(r, k) + \delta f(r, k, t)$ with $\delta f(r, k, t) = \exp(-i\omega t)(-\frac{\partial}{\partial \varepsilon}f_0(r, k))F(r, k) + c.c.$

For our purposes, it is sufficient to consider the zero temperature case, for which $(\delta f(r, k)) = \delta(\varepsilon_k + U(r) - \varepsilon_F)$, where $\varepsilon_F = 1/mv_F^2$ is the Fermi energy. Consequently the magnitude of the electron velocity $v(r)$ is defined by the grating potential according to $\frac{1}{2}mv(r)^2 + U(r) = \varepsilon_F$ and $F(r, k)$ becomes a function $F(r, n)$ of the unit vector $n = v/v(r)$. The current density (taking into account the two spin orientations) is $j(r) = e(m/\pi)v(r)(nF(r, n))$.

After linearization with respect to the electric field $\mathbf{E}$ one obtains a linear equation for $F$,

$$LF(r, n) = v(r)e\mathbf{E}(r)n, \quad (7)$$

where the operator $L$ is

$$L = -i\omega + \frac{1}{\tau} + v(r)n\nabla + (e\nabla v(r) + \omega_c)\frac{\partial}{\partial \varphi} - \frac{1}{\tau} \int \frac{d\varphi}{2\pi}.$$  

Here the angle $\varphi$ defines the direction of $n$, $\omega_c = |e|B/mc$ is the cyclotron frequency and $e = n \times \mathbf{B}/B$. To calculate the tensorial conductivity $\sigma_{s',s}$ we put $\mathbf{E}(r) = \mathbf{E}_0 \exp(i\mathbf{q}.r)$ and represent $F(r, n) = \sum s' \chi_{s',s}(n) \exp(i\mathbf{q}.r)$.

Consider now a periodic potential $U(r) = U_0 \cos(p_r)$. In the case of weak modulation $\eta \equiv U_0/\varepsilon_F \ll 1$ and one can perform a systematic expansion of Eq. (6) in $\eta$. This implies expanding the functions $v(r)$ and $\chi_{s',s}(n)$ and comparing in the resulting equation terms with the same spatial dependence and of the same order in $\eta$. One then finds that since the grating has only the first harmonic in $p$, the non-vanishing components of the tensorial conductivity are: $(s, s)$ to order $\eta^0$, $(s \pm 1, s)$ to order $\eta^1$, and $(s, s)$, $(s \pm 2, s)$ to order $\eta^2$.

The explicit expressions for the longitudinal conductivities are

$$\sigma_{s,s}^{(0)} = 2\sigma_0 \frac{\omega^2}{v_F q_s^2} \left[\frac{1}{i\omega \tau} + \langle G_s \rangle\right], \quad (8)$$

$$\sigma_{s \pm 1,s}^{(1)} = \eta\sigma_0 \frac{\omega^2}{2v_F q_s q_{s \pm 1}} i\varepsilon F \tau (G_{s \pm 1}d_{s \pm 1}G_s), \quad (9)$$

$$\sigma_{s,s}^{(2)} = \eta^2 \sigma_0 \frac{\omega^2}{8v_F q_s^2} (i\varepsilon F \tau)^2 \times \langle G_s d_{s+1}G_{s+1}d_{s+1}G_s + G_s d_{s+1}G_{s-1}d_{s-1}G_s \rangle. \quad (10)$$

(As is shown below, $(\epsilon^{-1})_{0,0}$ does not require the $(s \pm 2, s)$ elements of $\sigma^{(2)}$. To simplify the results the Fermi velocity is renormalized according to $v_F \rightarrow v_F(1 - \eta^2/16)$).

Here $\sigma_0 = (m/2\pi)e^2v_F^2\tau$ is the dc conductivity of a homogeneous 2DEG when $B = 0$ and the following operators are introduced: $d_s^\dagger = nq_s + kpe\partial/\partial \varphi$.

$$G_s = \left[1 - i\omega \tau + i\varepsilon F \tau nq_s + \omega_c \tau \frac{\partial}{\partial \varphi} - \int \frac{d\varphi}{2\pi}\right]^{-1}.$$  

The explicit calculation of the conductivity can be performed in terms of the integral representation of the operator $G_s$ given by

$$G_s g(\varphi) = R_s g(\varphi) + \frac{\langle R_s g \rangle}{1 - \langle R_s \rangle} R_s, \quad (12)$$

where the operator $R_s$ is defined by

$$R_s g(\varphi) = \gamma \int_{-\infty}^{\varphi} d\varphi' e^{K_s(\varphi, \varphi')} g(\varphi'), \quad (13)$$

with $K_s(\varphi, \varphi') = -\nu(\varphi - \varphi') - iz_s(\sin \varphi - \sin \varphi')$ and $\nu = (\tau^{-1} - i\omega)/\omega_c$, $\gamma = 1/\omega_c \tau$ and $z_s = q\varepsilon F/\omega_c$. The angles $\varphi$ and $\varphi'$ are counted from the direction of $n$ and $R_s$, $\langle R_s \rangle$ stand for $R_s 1$ and $\langle R_s \rangle 1$, respectively.

In what follows we consider a "fast" grating with a period shorter than the SAW length $\lambda$, i.e. $q \ll p$. (As an example, for $\omega/2\pi = 300MHz$ one has $\lambda = 9\mu m$ while $d$ varies from $0.1\mu m$ to $1\mu m$). In this case one can present the result of inverting the matrix $\epsilon$ in the following way
\( (\epsilon^{-1})_{0,0} = \frac{1}{1 + i\sigma_{\text{eff}}(\mathbf{q}, \omega)/\sigma_M} \) (14)

with \( \sigma_{\text{eff}}(\mathbf{q}, \omega) = \sigma(q, \omega) + \delta\sigma(q, \omega) \), where \( \sigma(q, \omega) \) is the longitudinal conductivity of a homogeneous 2DEG corresponding to wave vector \( q \) and frequency \( \omega \) and

\[
\delta\sigma(q, \omega) = \sigma_{(2),0}^{(2)} - \frac{\sigma_{0,0}^{(1)(1)}}{\sigma_{0,0}(0) - i(\eta_0/\eta_1)\sigma_M} - \frac{\sigma_{1,0}^{(1)}}{\sigma_{1,0}(0) - i(\eta_0/\eta_1)\sigma_M}. \tag{15}
\]

(Here \( \tilde{I} = -1 \)). The result (15) for \( \delta\sigma \) is valid up to the second order in \( \eta \), assuming \( \eta \) to be small. We will show below that nonetheless in the case \( \mathbf{q} \perp \mathbf{p} \) and for \( \omega_c \tau \gg 1 \), \( \delta\sigma \) can be comparable to \( \sigma \), since \( \delta\sigma/\sigma \propto \eta^2 (\omega_c \tau)^2 \). Eq. (15) is however correct even in this case, since the higher order terms are small, of order \( \eta^2 \), compared to \( \delta\sigma \).

Note that for a fast grating we have approximately \( q_1 = q_1 = p \) and \( \sigma_{1,1} = \sigma_{1,1}^{(0)} = \sigma(p, \omega) \), while \( \sigma_{0,0} = \sigma(q, \omega) \). As a result one can simplify Eq. (15) to obtain

\[
\delta\sigma(q, \omega) = \sigma_{(2),0}^{(2)} - \frac{\sigma_{0,0}^{(1)(1)}}{\sigma(p, \omega) - i(\eta_0/\eta_1)\sigma_M}. \tag{16}
\]

The conductivities of a homogeneous 2DEG are given by

\[
\sigma(q_s, \omega) \equiv \sigma_{s,s}^{(0)} = 2\sigma_0 \frac{\omega^2}{v_F q_s^2} \left[ \frac{1}{i\omega \tau} + \frac{\langle R_s \rangle}{1 - \langle R_s \rangle} \right], \tag{17}
\]

where

\[
\langle R_s \rangle = (\pi \gamma / \sinh \pi \nu) J_{\nu}(z_s) J_{-\nu}(z_s) \tag{18}
\]

and \( J_{\pm \mu}(z) \) are the Bessel functions.

We assume in addition that \( \lambda \) is longer than the cyclotron radius \( R_c = v_F/\omega_c \), i.e. \( z_0 = qv_F/\omega_c = qR_c \ll 1 \).

For \( B = 0.1 \)T and \( v_F = 1.3 \times 10^5 \)cm/sec the cyclotron radius \( R_c = 0.5 \mu m \), and for \( \omega / 2\pi = 300 \)MHz one finds \( qR_c = 0.3 \). Since the Weiss oscillations take place at \( pR_c \sim \pi n \) with \( n = 1, 2, \ldots \), the above assumption \( p \gg q \) implies that a considerable number of oscillations belongs to the region \( qR_c \ll 1 \).

In the case \( qR_c \ll 1 \) one finds from Eq. (17) the longitudinal conductivity of the homogeneous 2DEG to be

\[
\sigma(q, \omega) = \sigma_0 \frac{1 - i\omega \tau}{(1 - i\omega \tau)^2 + (\omega_c \tau)^2 + i(v_F \tau)^2/2\omega \tau}, \tag{19}
\]

while the correction \( \delta\sigma \), Eq. (16), is reduced to the form

\[
\delta\sigma(q, \omega) = \eta^2 \sigma_0 \frac{(\omega \tau)^2}{8(1 - \langle R \rangle)^2} \left[ \Phi_2 - \xi \Phi_1 \right]. \tag{20}
\]

The functions \( \Phi_{1,2} \) depend on \( \gamma, \nu, z = pR_c = 2\pi R_c/d \) and on the propagation direction of the SAW given by the angle \( \theta \) between \( q \) and \( p \).

\[
\Phi_1 = 2\frac{\gamma^2}{(\nu^2 + 1)^2} \frac{z(R_1)}{1 - \langle R_1 \rangle}^2 D_\nu(\theta), \tag{21}
\]

\[
\Phi_2 = \frac{\gamma \nu}{\nu^2 + 1} + \frac{\nu}{(\nu^2 + 1)^2} \frac{2z^2(R_1)}{1 - \langle R_1 \rangle} D_\nu(\theta), \tag{22}
\]

where

\[
D_\nu(\theta) = \cos^2 \theta - \nu^{-2} \sin^2 \theta. \tag{23}
\]

From Eqs. (21), (22) and (23) it follows that when \( q \perp p \) the grating induced part of the conductivity contains in addition to the small factor \( \eta^2 \) also a factor \( \omega_c \tau \) which can be large.

The function \( \xi \) is independent of the propagation direction

\[
\xi^{-1} = (1 - i\omega \tau) \left[ \frac{\langle R_1 \rangle}{1 - \langle R_1 \rangle} + \frac{1 + p\alpha_B/2}{i\omega \tau} \right]. \tag{24}
\]

where \( \alpha_B = e_o / mc^2 \) is the Bohr radius (equal 100Å for GaAs). Using Eq. (13) to calculate \( \langle R_0 \rangle \) and \( \langle R_1 \rangle \) in the functions \( \Phi_{1,2} \) and \( \xi \) one can find \( \delta\sigma(q, \omega) \) and the SAW propagation properties from Eqs. (4) and (3).

The Weiss oscillations are expected to be visible when \( \omega_c \tau \gg 1 \) and \( z = pR_c \gg 1 \). (For \( B = 0.1 \)T and \( \tau = 150 \)ps one finds \( \omega_c \tau = 40 \). We assume in addition that \( \omega \tau \ll 1 \). (For \( \omega / 2\pi = 300 \)MHz with \( \tau = 150 \)ps one finds \( \omega \tau \approx 0.3 \). With these approximations (when \( \gamma = \nu = (\omega_c \tau)^{-1} \ll 1 \) the results are more transparent.

The longitudinal conductivity with no grating is given now by

\[
\sigma(q, \omega) = \frac{\sigma_0}{(\omega_c \tau)^2} \left[ 1 + i(qR_c)^2/2\omega \tau \right]^{-1}. \tag{25}
\]

Note that \( \sigma_0 / (\omega_c \tau)^2 \) is the "dc conductivity" at strong magnetic fields, which is obtained upon solving the kinetic equation with an electric field constant in time and homogeneous in space. This "dc conductivity" corresponds to the condition \( (qR_c)^2 / 2\omega \tau \ll 1 \), which is not always satisfied in SAW measurements.

In the assumed range of parameters, the term \( \xi \Phi_1 \) in Eq. (20) can be neglected compared to \( \Phi_2 \), yielding

\[
\delta\sigma(q, \omega) = \sigma_{0,0}^{(2)} - \frac{\eta^2 \sigma_0}{8(\omega_c \tau)^2} \left[ 1 + i(qR_c)^2 / 2\omega \tau \right]^{-2} \times \{-1 + \phi(z) \left[ \cos^2 \theta - (\omega_c \tau)^2 \sin^2 \theta \right]\}. \tag{26}
\]

with

\[
\phi(z) = 2z^2 J_0^z(z)/[1 - J_0^z(z)]. \tag{27}
\]

These results demonstrate that the effect of the grating and hence also the amplitude of the Weiss oscillations is stronger by a factor of \( (\omega_c \tau)^2 \) when the SAW propagates perpendicular to the grating, \( E^0 \parallel \mathbf{q} \perp \mathbf{p} \), compared to
the case of parallel propagation, $E_0 \parallel q \parallel p$. This is because in the “perpendicular” geometry the grating affects the Hall current, which is stronger. In the limit $q \to 0$ Eq. (26) reduces to the result for the dc magnetoconductivity derived in [12].

\[ \Gamma \propto \frac{2R_c}{d} \]

\[ \Delta v/v \propto \frac{2R_c}{d} \]

FIG. 1. Absorption coefficient $\Gamma$ of SAW as a function of the magnetic field for the transverse orientation, $p \perp q$ and the following values of the parameters: density $n_e = 1 \cdot 10^{11}$ cm$^{-2}$, $\omega = 2\pi \cdot 300$ MHz, $\tau = 150$ ps, $d = 300$ nm. The strength of the grating $\eta$ is equal to (from the top to the bottom): 0 (no grating), 0.01, 0.02, 0.03, and 0.05.

FIG. 2. Velocity shift $\Delta v/v$ of SAW as a function of the magnetic field. The values of all the parameters are the same as in Fig.1.

We have evaluated numerically the attenuation and the velocity change according to Eqs. (4), (5), (14), and (20) using typical experimental parameters in the regime $d, R_c \ll \lambda$. The results are shown in Figs. 1 and 2 for the orientation $q \perp p$. In this case the oscillations amplitude is proportional to $(\omega_\tau)^2 \eta^2$ (see Eq. (26) for $\theta = \pi/2$), which can be large even for small $\eta$. This is demonstrated in the figures, where $\eta = 0.01$ is sufficient to produce strong oscillations ($\omega_\tau$ is as large as 100 at $B = 0.25$ T). For the parallel orientation $q \parallel p$ ($\theta = 0$) the factor of $(\omega_\tau)^2$ is absent in (26) and the amplitude of oscillations is proportional to $\eta^2$ and thus small for weak modulation.

Let us mention that in high mobility samples the impurity potential is smoothly varying and the scattering probability is not isotropic, but rather peaked in the forward direction. This will strongly affect the damping of the oscillations with high oscillation number $2R_c/d \gg 1$, but will not be very important for the first few oscillations with $2R_c/d \sim 1$.

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