Collective excitations spectrum of a density modulated quasi-one-dimensional electron gas in a magnetic field

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We determine the collective excitations spectrum and discuss the numerical results for a parabolically confined density modulated quasi-one-dimensional electron gas in the presence of an external magnetic field. We derive the inter- and intra-band magnetoplasmon spectrum within the self-consistent-field approach. In this work we focus on magnetoplasmon oscillations in this system and as such results are presented for the intra-Landau-band magnetoplasmon spectrum that exhibits oscillatory behavior, these oscillations are not with constant period in $1/B$ and are significantly effected at low B and corresponding high $1/B$.

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I. COLLECTIVE EXCITATION SPECTRUM OF DENSITY MODULATED ONE-DIMENSIONAL ELECTRON GAS (DM1DEG)

In the last couple of decades or so remarkable progress has been made in epitaxial crystal growth techniques which have made possible the fabrication of semiconductor heterostructures. These modern microstructuring techniques can be used to laterally confine quasi-two-dimensional electron gas (2DEG) in, e.g., GaAs/AlGaAs heterostructure on a submicrometer scale to quasi-one-dimensional structures (quantum wires) or quasi-zero-dimensional quantum dots. The system that we are considering in the present work can be realized by various methods, e.g., the application of a laterally microstructured gate electrode and the holographic illumination technique which allow for a tunable periodic density modulation of the quasi-one-dimensional electron gas.

There have been a number of approaches to study collective excitations spectrum of a quasi-two- and one-dimensional electron gas (1DEG) systems theoretically[1–9] and experimentally.[10–14] We extend the theoretical work by calculating the inter- and intra-Landau band magnetoplasmon spectrum of a density modulated quasi-one-dimensional electron gas (DM1DEG) in the presence of a perpendicular magnetic field using the self-consistent-field (SCF) approach and focus on the oscillatory behavior of the intra-Landau band magnetoplasmons. In this context, the term "1D" means that we start with the original 2DEG in x-y plane. We apply a confining potential in the x direction leaving the y direction free. A magnetic field is applied along the z direction perpendicular to the x-y plane of the original 2DEG. The collective particle energy spectrum, $E_{ij}(k_y)=\hbar^2k_y^2/2m*+E_x^i$ consists of energetically separated 1D subbands formed due to lateral confining potential along the x direction. The electron wave vector k_y characterizes the free motion in the y direction.

The effect of density modulation is to broaden the Landau levels into minibands whose width oscillates as a function of the magnetic field strength. The electronic states are thus substantially altered, resulting in modulated density of states, as shown by magnetocapacitance measurements[13,14] of the quasi-two-dimensional systems. Behavior akin to this is expected for the quasi-one-dimensional system under consideration. The density of states affects many response and transport phenomena as well as thermodynamic properties. Of these, one of the most important properties is the collective excitation spectrum and we evaluate the dynamic, nonlocal dielectric response function to study it. As we show in our work for a quasi-one-dimensional system, magnetoplasma spectrum significantly exhibits modulation of the electronic density-of-states as oscillating magnetoplasma frequencies. As we discuss in detail, this result is obtained in the regime of weak modulation and long wavelength thus we do not find this result discussed in Ref. 9. Another condition for the observation of these oscillations is that the coupling between intra-Landau band mode and inter-Landau band mode must be small. Mixing of these modes can be minimized by controlling the degree of density modulation and by applying an appropriate magnetic field and confinement potential.

II. FORMULATION

Our system is a density modulated quasi-one dimensional electron gas (DM1DEG) built on a two-dimensional electron gas (2DEG) by inducing another effective confining potential $\frac{1}{2}(m*\omega_0^2x^2)$ along the x direction which is assumed to be parabolic. The magnetic field is perpendicular to the x-y plane in which electrons with unmodulated areal density n_D, effective mass $m*$, and charge $-e$ are confined. We employ the Landau gauge and write the vector potential as $A=(0,Bx,0)$. The two-dimensional Schrödinger equation with parabolic confining potential in the Landau gauge is ($\hbar=c=1$ here)

$$H_0=\frac{1}{2m*}\left[-\frac{\partial^2}{\partial x^2}+\left(-i\frac{\partial}{\partial y}+\frac{e}{c}Bx\right)^2\right]+\frac{1}{2}(m*\omega_0^2x^2). \tag{1}$$

Since the Hamiltonian does not depend on the y coordinate, the unperturbed wave functions are plane waves in the y direction. This allows us to write for the wave functions,

$$\phi_{nk_y}(\overline{x}) = \frac{1}{\sqrt{L_y}} e^{ik_y y} u_{nk_y(x)}, \tag{2}$$

with L_y being a normalization length in the y direction and $\overline{x}$ a 2D position vector on the x-y plane. Substitution of the above form of the wave function into Eq. (1), yields

$$H_0 = -\frac{1}{2m^*}\frac{\partial^2}{\partial x^2} + \frac{1}{2}m^*\Omega_0^2(x-x_0)^2 + \frac{k_y^2}{2m^*(B)}, \tag{3}$$

with $(\Omega_0^2=\omega_c^2+\omega_0^2, l^2(B)=l^2\omega_c^2/\Omega_0^2)$, where $\omega_c=eB/m^*$ is the cyclotron frequency, $x_0=-l^2(B)k_y=-\omega_c k_y/m^*\Omega_0^2$, is the coordinate of cyclotron orbit center and $l(B)$ is the magnetic length, $m^*(B)=m^*(\Omega_0^2/\omega_0^2)$ is the normalized effective mass. In the x direction, the Hamiltonian has the form of a harmonic oscillator Hamiltonian. Hence we can write the unmodulated eigenstates in the form $\phi_{nk_y}(\overline{x})=1/\sqrt{L_y}e^{ik_y y}u_{nk_y(x;x_0)}$, with $u_{nk_y(x;x_0)}=(\sqrt{\pi}2^n n!\, l)^{-1/2}$ $\times\exp[-1/2l^2(x-x_0)^2]H_n(x-x_0/l)$, where $u_{nk_y(x;x_0)}$ is a normalized harmonic oscillator wave function centered at x_0 and $H_n(x)$ are Hermite polynomials[15] with n the Landau level quantum number. The energy of nth Landau level (unperturbed Hamiltonian H_0) is

$$\varepsilon_n^{(0)} = (n+1/2)\Omega_0 + \frac{k_y^2}{2m^*(B)}. \tag{4}$$

In the presence of modulation, the Hamiltonian is augmented by the term $H'=V_0\cos((2\pi/a)x)$, where V_0 is the amplitude of the modulation and is about an order of magnitude smaller than Fermi energy (V_0/ε_F). Due to the smallness of V_0 we employ first order (in H') perturbation theory in the evaluation of the energy eigenvalues using the unperturbed wave functions. The correction to the unperturbed eigenenergies with a new variable $y=x-x_0/l$, is given by

$$\varepsilon_n^{(1)} = \frac{2V_0}{\sqrt{\pi}2^n n!}\cos\left(\frac{2\pi}{a}x_0\right)\int_0^a dy\,\exp(-y^2) \times[H_n(y)]^2\cos\left(\frac{2\pi}{a}ly\right).$$

The integral in above equation is given by Gradshteyn-Ryzhik[16] (page 841, No. 7.388.5); and the result is

$$\varepsilon_n^{(1)} = V_n\cos\left(\frac{2\pi}{a}x_0\right), \tag{5}$$

where $V_n=V_0\exp(-X/2)L_n(X), X=(2\pi/a)^2\omega_c/2m^*\Omega_0^2$, and $L_n(x)$ is a Laguerre polynomial. By combining Eqs. (4) and (5) we write, for the energy eigenvalues to first order in H'

$$\varepsilon(n,x_0) = (n+1/2)\Omega_0 + \frac{k_y^2}{2m^*(B)} + V_n\cos\left(\frac{2\pi}{a}x_0\right). \tag{6}$$

The above equation shows that the formerly sharp Landau levels, Eq. (4), are now broadened into minibands by the modulation potential. Furthermore, the Landau bandwidth $(\sim|V_n|)$ oscillate as a function of n, since $L_n(X)$ is an oscillatory function of its index.[15]

III. DENSITY-DENSITY CORRELATION FUNCTION OF A DM1DEG IN A MAGNETIC FIELD

The dynamic and static response properties of an electron system are all embodied in the structure of the density-density correlation function. We employ the Ehrenreich-Cohen self-consistent-field (SCF) approach[17] to calculate the density-density correlation function. The SCF treatment presented here is by its nature a high density approximation which has been successful in the study of collective excitations in lower-dimensional systems such as planar semiconductor superlattices[18] and quantum wire structures,[5,12,19] both with and without an applied magnetic field. Such success has been convincingly attested by the excellent agreement of SCF predictions of plasmon spectra with experiments.

Following the SCF approach, the density response of electrons due to a perturbing potential is given by

$$\delta n(\overline{x}_0,z_0;t) = \sum_{\alpha\alpha'}\frac{f(\varepsilon_{\alpha'})-f(\varepsilon_\alpha)}{\varepsilon_{\alpha'}-\varepsilon_\alpha+\omega+i\eta}\langle\alpha|V(\overline{x},z;\omega)|\alpha'\rangle \times\langle\alpha'|\delta(\overline{x}-\overline{x}_0)\delta(z-z_0)|\alpha\rangle, \tag{7}$$

where $V(\overline{x},z;\omega)$ is the self-consistent potential and α stands for the quantum numbers n and k_y. Fourier transforming on the x-y plane we obtain the induced particle density

$$\delta n(\overline{q},z_0;\omega) = \frac{1}{A}\delta(z)V(\overline{q},z=0;\omega)\sum_{\alpha\alpha'}\frac{f(\varepsilon_{\alpha'})-f(\varepsilon_\alpha)}{\varepsilon_{\alpha'}-\varepsilon_\alpha+\omega+i\eta} \times|\langle\underline{\alpha}'|e^{-i\overline{q}.\overline{x}}|\underline{\alpha}\rangle|^2,$$

where A denotes the area of the system. We can perform the k_y' sum in the above equation to obtain

$$\delta n(\overline{q},z;\omega) = \frac{1}{A}\delta(z)V(\overline{q},z=0;\omega)\times\sum_{n,n',k_y}C_{nn'} \times\left(\frac{\overline{q}^2\omega_c}{2m^*\Omega_0^2}\right)\frac{f[\varepsilon(n',k_y-q_y)]-f[\varepsilon(n,k_y)]}{\varepsilon(n',k_y-q_y)-\varepsilon(n,k_y)+\omega+i\eta}. \tag{8}$$

Writing the induced particle density as $\delta n(\overline{q},z;\omega)=\delta n(\overline{q},\omega)\delta(z)$, allows us to rewrite Eq. (8) as $\delta n(\overline{q},\omega)=V(\overline{q},\omega)\Pi_0(\overline{q},\omega)$: where $V(\overline{q},\omega)=V(\overline{q},z=0;\omega)$ and $\Pi_0(\overline{q},\omega)$ is the density-density correlation function of the noninteracting electron system, given by

$$\Pi_0(\overline{q},\omega) = \frac{1}{A}\sum_{n,n'}\sum_{k_y}C_{nn'}\left(\frac{\overline{q}^2\omega_c}{2m^*\Omega_0^2}\right) \times\frac{f[\varepsilon(n',k_y-q_y)]-f[\varepsilon(n,k_y)]}{\varepsilon(n',k_y-q_y)-\varepsilon(n,k_y)+\omega+i\eta}, \tag{9}$$

where

$$C_{nn'}(x) = \frac{n_2!}{n_1'!}e^{-x}x^{n_1-n_2}[L_{n_2}^{n_1-n_2}(x)]^2$$

with $n_1=\max(n,n')$, $n_2=\min(n,n')$, and $L_n'(x)$ an associated Laguerre polynomial. The induced potential V^{ind} is related to the density response δn by Poisson's equation

$$\nabla^2 V^{\text{ind}}(\bar{x},z;t) = -\frac{4\pi e^2}{k}\delta n(\bar{x},z;t), \tag{10}$$

where k is the background dielectric constant. The above equation can be solved to yield

$$V^{\text{ind}}(\bar{q},\omega) = \frac{2\pi e^2}{k\bar{q}}\delta n(\bar{q},\omega). \tag{11}$$

Recalling that the self-consistent potential, $V(\bar{q},\omega) = V^{\text{ext}}(\bar{q},\omega) + V^{\text{ind}}(\bar{q},\omega)$, is the sum of the external and induced potentials, multiplying both sides by $\Pi(\bar{q},\omega)$ and solving for $\delta n(\bar{q},\omega)$ yields

$$\delta n(\bar{q},\omega) = \Pi(\bar{q},\omega)V^{\text{ext}}(\bar{q},\omega), \tag{12}$$

where

$$\Pi(\bar{q},\omega) = \frac{\Pi_0(\bar{q},\omega)}{1 - v_c(\bar{q})\Pi_0(\bar{q},\omega)} \tag{13}$$

is the density-density correlation function of the interacting system with $v_c(\bar{q}) = 2\pi e^2/k\bar{q}$ the 2D Coulomb potential. Making use of the transformation $k_y \to -k_y$ with the fact that $\varepsilon(n,k_y)$ is an even function of k_y, and at the same time interchanging $n \leftrightarrow n'$ we write for the noninteracting density-density correlation function Eq. (8)

$$\Pi_0(\bar{q},\omega) = \frac{m^* \Omega_0^2}{\pi a \omega_c}\sum C_{nn'}\left(\frac{\vec{q}^2\omega_c}{2m^*\Omega_0^2}\right)\int_0^a dx_0\{f[\varepsilon(n,x_0 + x_0'\,] - f[\varepsilon(n',x_0)]\} \times [\varepsilon(n,x_0 + x_0') - \varepsilon(n',x_0) + \omega + i\eta]^{-1}. \tag{14}$$

In writing the above equation we converted the k_y sum into an integral over x_0. $f(E)$ is the Fermi-Dirac distribution function, $x_0 = -k_y\omega_c/m^*\Omega_0^2$ and $x_0' = -q_y\omega_c/m^*\Omega_0^2$.

The above Eqs. (13) and (14) will be the starting point of our examination of the inter- and intra-Landau band plasmons. The form of the expressions for the real and imaginary part of the density-density correlation function makes the even and odd (in frequency ω) properties of these functions very apparent. These functions are the essential ingredients for theoretical considerations of such diverse problems as high frequency and steady state transport, static and dynamic screening, and correlation phenomena.

The plasma modes are readily furnished by the singularities of the function $\Pi(\bar{q},\omega)$, from the roots of the longitudinal plasmon dispersion relation obtained from Eq. (13) as

$$1 - v_c(\bar{q})\,\text{Re}\,\Pi_0(\bar{q},\omega) = 0 \tag{15}$$

along with the condition $\text{Im}\,\Pi_0(\bar{q},\omega) = 0$ to ensure long-lived excitations. The roots of Eq. (15) give the plasma modes of the system.

$$1 = \frac{2\pi e^2}{k\bar{q}}\frac{m^*\Omega_0^2}{\pi a\omega_c}\sum_{n,n'} C_{nn'}\left(\frac{\vec{q}^2\omega_c}{2m^*\Omega_0^2}\right)[I(\omega) + I(-\omega)], \tag{16}$$

with

$$I(\omega) = P\int_0^a dx_0 \frac{f[\varepsilon(n,x_0)]}{+\omega - \varepsilon(n,x_0) + \varepsilon(n',x_0 + x_0')},$$

where P is the principal value.

The plasma modes originate from two kinds of electronic transitions, those involving different Landau bands (inter-Landau band plasmons) and those within a single Landau band (intra-Landau band plasmons). Inter-Landau band plasmons involve the local 1D magnetoplasma mode and the Bernstein-like plasma resonances,[20] all of which involve excitation frequencies greater than the Landau-band separation ($\sim\Omega_0$). On the other hand, intra-Landau band plasmons resonate at frequencies comparable to the bandwidths, and the existence of this new class of modes is due to finite width of the Landau levels. These magnetoplasmons in a quasi-one-dimensional system have been analyzed in detail elsewhere.[9] We will concentrate on the oscillatory behavior of these magnetoplasmons. The occurrence of such intra-Landau band plasmons is accompanied by SdH type of oscillatory behavior[2,21] in $1/B$. These oscillations[2,22] are not with constant period in $1/B$ (which exhibits significant effect for small value of B and corresponding large value of $1/B$) due to confinement potential acting in the x direction and also show the depopulation, and cross over effects[8] on magnetoplasmons from density modulated two-dimensional electron gas (DM2DEG) (Ref. 23) to density modulated one-dimensional electron gas (DM1DEG).

SdH type of oscillations result from the emptying out of electrons from successive Landau bands when they pass through the Fermi level as the magnetic field is increased. The amplitude of the SdH type of oscillations is a monotonic function of magnetic field, when the Landau bandwidth is independent of the band index n. In DM1DEG considered here, the Landau bandwidths oscillate as a function of the band index n. It is to be expected that such oscillating bandwidths would effect the plasmon spectrum of the intra-Landau band type, resulting in another type of oscillation. These oscillations are not with constant period in $1/B$, because at a small value of B and corresponding large value of $1/B$ cyclotron diameter exceeds the characteristic length of the confining potential.

For the excitation spectrum, we need to numerically solve Eq. (15) for all vectors, frequencies, magnetic field, and confinement potential. We will consider the case of weak modulation ($V_0/E_F \ll 1$) and long wavelength. In these limits we can solve Eq. (16) analytically for zero temperature. We expand the coefficient $C_{nn'}(\vec{q}^2\omega_c/2m\Omega_0^2)$ to lowest order in its argument with the result

$$1 = \frac{2\pi e^2}{km^*}\underline{q}\frac{1}{\omega^2 - \Omega_0^2}\left(\frac{m\Omega_0}{\pi a}\sum_n f(\varepsilon_n)\right). \tag{17}$$

The term in parentheses is easily recognized as the unmodulated particle density $n_D = (m\Omega_0/\pi a)\Sigma_n f(\varepsilon_n)$, where n is the sum over all occupied Landau bands. Defining the plasma frequency through $\omega_{p,D}^2 = (2\pi n_D e^2/km)\bar{q}$, we finally obtain the inter-Landau band plasmon dispersion relation $1 = \omega_{p,D}^2/\omega^2 - \Omega_0^2$ or $\omega^2 = \Omega_0^2 + \omega_{p,D}^2$, which is the ordinary one-dimensional plasmon dispersion relation.

The intra-Landau band plasmon dispersion relation for zero temperature reduces to $1=\tilde{\omega}^2/\omega^2$, where

$$\tilde{\omega}^2 = \frac{8e^2}{k\overline{q}}\frac{m^*\Omega_0^2}{\pi a\omega_c}\sin^2\left(\frac{\pi}{a}(x_0')\right) \times \sum_n |V_n|\sqrt{1-\Delta_n^2}\theta(1-\Delta_n), \tag{18}$$

with $A_n=(a/2\pi)(|V_n|/V_n)\sqrt{1-\Delta_n^2}\theta(1-\Delta_n)$, $\Delta_n=|\varepsilon_F-\varepsilon_n/V_n|$, $\theta(x)$ the Heaviside unit step function.

We have derived the expression for $\tilde{\omega}$ [Eq. (18)] under the condition $\omega \gg |\varepsilon(n,x_0+x_0')-\varepsilon(n,x_0)|$ as $x_0'\to 0$ which leads to a relation between the frequency and the Landau level broadening $\omega \gg |2V_n \sin((\pi/a)x_0')\sin[(2\pi/a)(x_0+x_0'/2)]|$. This ensures that $\mathrm{Im}\,\Pi_0(\overline{q},\omega)=0$ and the intra-Landau-band magnetoplasmons are undamped. For a given V_n, this can be achieved with a small but nonzero q_y (recall that $x_0'=-q_y\omega_c/m^*\Omega_0^2$).

In general, the inter- and intra-Landau band modes are coupled for arbitrary magnetic field strengths. The general dispersion relation is

$$1 = \frac{\omega_{p,D}^2}{\omega^2-\Omega_0^2} + \frac{\tilde{\omega}^2}{\omega^2}.$$

This equation yields two modes which are given by

$$\omega_\pm^2 = \frac{1}{2}(\Omega_0^2+\omega_{p,D}^2+\tilde{\omega}^2) \pm \frac{1}{2}\{(\Omega_0^2+\omega_{p,D}^2+\tilde{\omega}^2+2\Omega_0\tilde{\omega}) \times (\Omega_0^2+\omega_{p,D}^2+\tilde{\omega}^2-2\Omega_0\tilde{\omega})\}^{1/2},$$

which reduces to

$$\omega_+^2 = \Omega_0^2+\omega_{p,D}^2,$$

and

$$\omega_-^2 = \tilde{\omega}^2,$$

with corrections of order $\tilde{\omega}^2/\Omega_0^2$ and $\tilde{\omega}^2/\omega_{p,D}^2$. So long as $|V_n|<\Omega_0$, mixing of the inter- and intra-band modes is small. Only the intra-Landau band mode ($\tilde{\omega}$) will be excited in the frequency regime $\Omega_0>\omega\sim|V_n|$. We now present the results for the oscillatory behavior of the intra-Landau band magnetoplasmons as a function of $1/B$ and the confinement energy.

IV. NUMERICAL RESULTS AND DISCUSSION

The intra-Landau band plasma frequency given by Eq. (18) is shown graphically in Fig. 1 as a function of $1/B$ for two different values of confinement energy, using parameters:[2,5,11] $m^*=0.07m_e$, $k=13.6$, $n_D=6\times10^{15}$ m^{-2}, $a=500$ nm, and $V_0=1.0$ meV; also we take $q_x=0$ and $q_y=0.01k_F$, with $k_F=(2\pi n_D)^{1/2}$ being the Fermi wave number of the unmodulated 1DEG in the absence of magnetic field. The modulation induced oscillations are apparent, superimposed on SdH-type oscillations. These oscillations are not with constant period in $1/B$ (which exhibits a significant effect for a small value of B and a corresponding large value of $1/B$) due to confinement potential acting in the x direction. They have longer period and much reduced amplitude. It must be noted that this result is obtained in the regime of weak modulation and long wavelength. Another condition for the observation of these oscillations is that the coupling between inter-Landau band mode and intra-Landau band mode must be small. These modes involve different energy scales $\omega>\Omega_0$ for the former and $\omega\sim|V_n|<\Omega_0$ for the latter. Mixing of these modes can be minimized by controlling the degree of density modulation and by applying an appropriate magnetic field and confinement potential.

The origin of two types of oscillations can be understood by a closer analytic examination of Eq. (18). In the regime $\Omega_0>|V_n|$, the unit step function vanishes for all but the highest occupied Landau band, corresponding, say, to the band index N. The sum over n is trivial, and plasma frequency is given as $\tilde{\omega}^2=|V_N|^{1/2}(1-\Delta_N^2)^{1/4}\theta(1-\Delta_N)$. The analytic structure primarily responsible for the SdH type of oscillations is the function $\theta(1-\Delta_N)$, which jumps periodically from zero

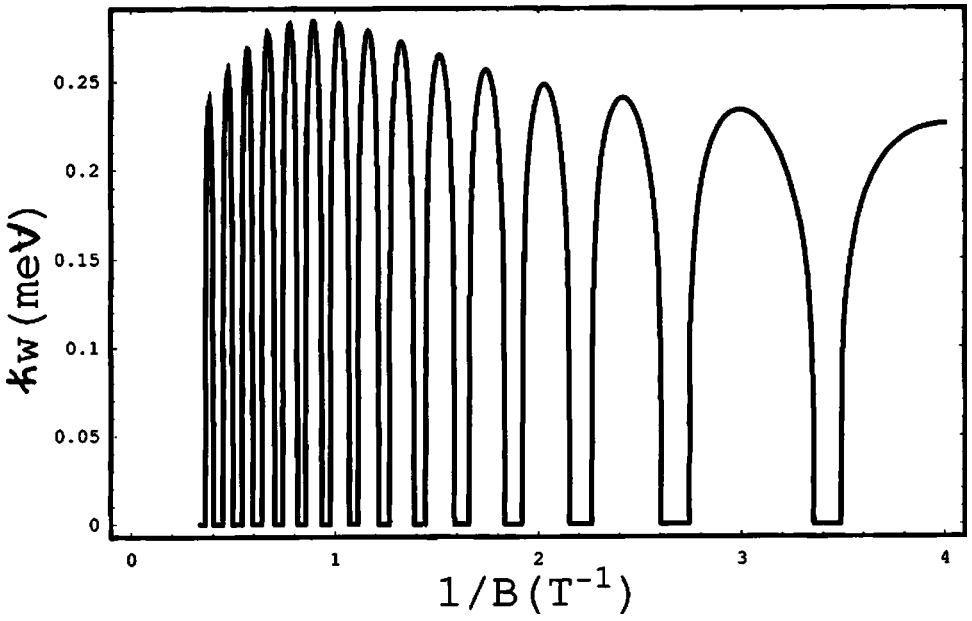

FIG. 1. Intra-Landau band plasma frequency as a function of inverse magnetic field for confinement energy (1 meV).

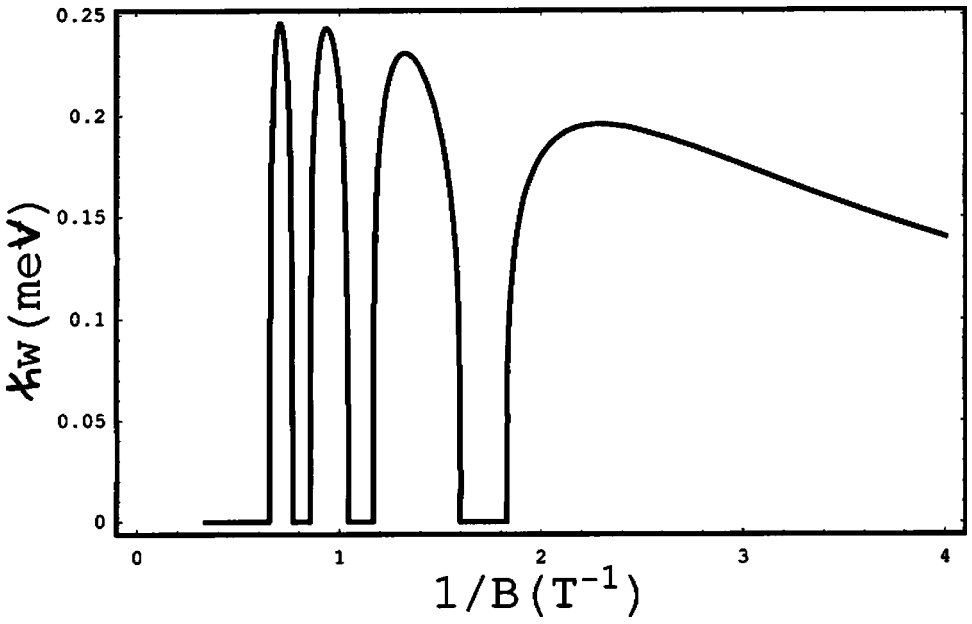

FIG. 2. Intra-Landau band plasma frequency as a function of inverse magnetic field for confinement energy (2 meV).

(when the Fermi level is above the highest occupied Landau band) to unity (when the Fermi level is contained within the highest occupied Landau band). On the other hand, the periodic modulation of the amplitude of the SdH-type oscillations shown in Figs. 1 and 2 is due to the oscillatory nature of the factor $|V_N|^{1/2}$, which has been shown in a two-dimensional system to exhibit commensurability oscillations.[6,13,22,24] In our case, these oscillations are not with constant period in $1/B$. This clearly indicates the one-dimensional character of our theory. In a DM2DEG the number of occupied Landau levels increases with decreasing B, leading, ideally, to an infinite number of SdH type of oscillations periodic in $1/B$.[23] In a 1DEG system however, only a finite number of 1D subbands are occupied at $B=0$, giving rise to a finite number of SdH type of oscillations and deviations from the $1/B$ period, because with increasing B the 1D density of states increases and the hybrid 1D subband Landau levels are depopulated.[4,14,25,26] In the extreme 2D regime ($\omega_0 \ll \omega_c$), the Fermi energy goes to the bottom of the 1D Landau subband. If we lower the confinement potential the magnetic confinement overcomes the potential confinement, hence we are in the original 2D regime.[23] On the other hand if we increase the confinement potential, the confinement potential overcomes the magnetic confinement and we have a crossover[13] from a two-dimensional system to a one-dimensional system. In Figs. 1 and 2 we have plotted the intra-Landau band plasma frequency as a function of the inverse magnetic field for two different confinement energies given by Eq. (18).

V. CONCLUSION

We have determined the intra-Landau band plasmon frequency for a density modulated quasi-one-dimensional electron gas in the presence of a magnetic field employing the SCF approach. Furthermore, we have seen the oscillations of the intra-Landau band plasma frequency in 1D regime as a function of B^{-1}, their origin lies in the interplay of the three physical length scales of the system, i.e., the modulation period, confinement length, and cyclotron diameter at the Fermi level. When a strong magnetic field is applied, our model recovers complete Landau quantization and for a very high magnetic field our results are comparable with extreme 2D regime ($\Omega_0 \ll \omega_c$).

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