IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Surface polaritons in a GaAs/AlGaAs heterojunction in a high magnetic field

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

1998 J. Phys.: Condens. Matter 10 5781

(http://iopscience.iop.org/0953-8984/10/26/006)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 171.66.16.209
The article was downloaded on 14/05/2010 at 16:33

Please note that terms and conditions apply.

J. Phys.: Condens. Matter **10** (1998) 5781–5790. Printed in the UK PII: S0953-8984(98)90922-5

Surface polaritons in a GaAs/AlGaAs heterojunction in a high magnetic field

N N Beletskii†, G P Berman‡, A R Bishop‡ and S A Borisenko†

† Institute for Radiophysics and Electronics of the NAS of the Ukraine, 12, Academician Proskury Street, Kharkov, 310085, Ukraine

‡ Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Received 21 January 1998, in final form 16 April 1998

Abstract. The spectrum of the surface polaritons (SP) in a GaAs/AlGaAs heterojunction in the presence of a large transverse quantizing magnetic field is calculated under the quantum Hall effect conditions. The dispersion properties of the SPs are studied taking into consideration the values of the dielectric constants of the GaAs and the $Al_xGa_{1-x}As$ media, and the finite thickness, d, of the $Al_xGa_{1-x}As$ layer. It is shown that in the vicinity of the electron cyclotron resonance, the SPs become slow waves, and their group velocity exhibits stepwise behaviour. The magnitude of these steps is determined by the fine-structure constant, $\alpha = e^2/\hbar c$, the thickness d of the $Al_xGa_{1-x}As$ layer, and the dielectric constants of GaAs and $Al_xGa_{1-x}As$. It is found that the values of the phase and the group velocities of the SPs can significantly decrease with increasing thickness, d, of the $Al_xGa_{1-x}As$ layer and with increasing difference between the dielectric constants of GaAs and $Al_xGa_{1-x}As$. Numerical results for the dispersion curves are presented for representative cases. The possibility of experimental observation of the effects considered is discussed.

1. Introduction

Due to significant progress in crystal-growth techniques, including molecular-beam epitaxy and metal–organic chemical vapour deposition, the interest in collective electromagnetic excitations in two-dimensional electron systems (2DES) has increased significantly. There is special interest in the surface polaritons (SP) which are non-radiative electromagnetic waves localized at the 2DES [1–3].

Applying an external magnetic field, $\boldsymbol{B}$, perpendicular to the 2DES has important consequences. For instance, the phase velocity, $v_{ph} = \omega/k$, and the group velocity, $v_g = \partial\omega/\partial k$, of the SPs decrease dramatically in the neighbourhood of the cyclotron resonance (CR) (ω and k are the frequency and the in-plane component of the wave vector of the SPs, respectively) [4]. In this case, the SPs can become slow waves. Of significant interest are the properties of the SPs in high magnetic fields, under the conditions which produce the integer quantum Hall effect [5, 6]. In this case, all of the components of the conductivity tensor of the 2DES are quantized, i.e. they exhibit stepwise behaviour as the magnetic field varies. As a result, the dispersion characteristics of the SPs are also quantized. In particular, when the magnitude of the magnetic field varies, the SP group velocity exhibits a stepwise behaviour in the vicinity of the CR. The magnitude of the steps is proportional to the fine-structure constant, $\alpha = e^2/\hbar c$, where e is the electron charge, and c is the velocity of light.

 © 1998 IOP Publishing Ltd

Note that the dispersion properties of the SPs were investigated under the assumption that a 2DES is placed into an infinite homogeneous medium with the dielectric constant ε [5, 6]. In fact, the real picture is more complicated. Also, a selectively doped $Al_xGa_{1-x}As$ layer has a finite thickness. As a result, the electrons which form the 2DES are located between a GaAs layer (this layer forms the substrate, and its thickness can be considered to be infinite) and a $Al_xGa_{1-x}As$ layer. In addition, the dielectric constants of GaAs and $Al_xGa_{1-x}As$ are different [7, 8]. In [7, 8], the ratio of the dielectric constants of the $Al_xGa_{1-x}As$ and the GaAs was chosen to be 0.95. These parameters determine the behaviour of the SPs in the GaAs/$Al_xGa_{1-x}As$ heterojunction.

In this paper, we investigate the SPs in a 2DES under the quantum Hall effect conditions, taking into account the finite thickness of the $Al_xGa_{1-x}As$ layer and the difference between the dielectric constants of GaAs and $Al_xGa_{1-x}As$.

The paper is organized as follows. In section 2, we derive the dispersion relation for the SPs in a GaAs/$Al_xGa_{1-x}As$ heterojunction in a transverse quantizing magnetic field. In this section, some limited cases of the dispersion relation are discussed. In section 3, numerical results are presented and analysed for some representative cases. Section 4 concludes the paper with a brief summary of the results obtained and a discussion of the possibility of experimental observation of the properties considered for the SPs in the GaAs/$Al_xGa_{1-x}As$ heterojunction.

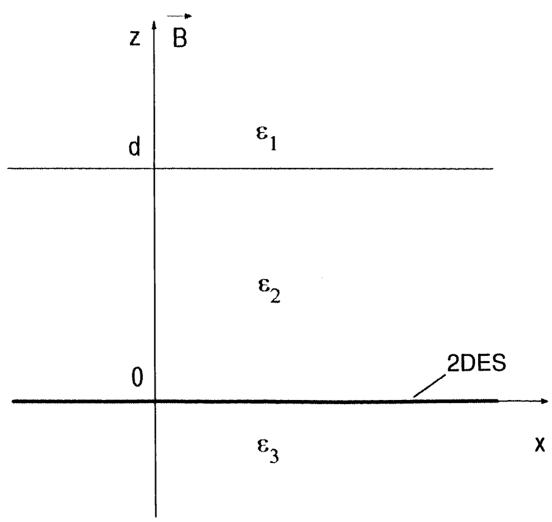

Figure 1. The geometry of the system. The semi-infinite medium 1 is the vacuum/air with the dielectric constant $\varepsilon_1 = 1$; medium 2 is the $Al_xGa_{1-x}As$ layer with the dielectric constant ε_2; the semi-infinite medium 3 is the GaAs layer with the dielectric constant ε_3.

2. Electrodynamics of the GaAs/AlGaAs heterojunction in a high magnetic field

We consider a structure consisting of two semi-infinite media, 1 ($z > d$) and 3 ($z < 0$), with the dielectric constants ε_1 and ε_3, respectively, separated by a thin layer (medium 2) with the thickness d and the dielectric constant ε_2 (see figure 1). Suppose that the media 2 and 3 form a heterojunction at the interface $z = 0$, i.e. at this interface a 2DES is formed. The external quantizing magnetic field, $\boldsymbol{B}$, is directed perpendicularly to the 2DES, along the

z-axis. We assume that the process of propagation of the SPs in a 2DES is non-radiative, i.e. in the media 1 and 3 the electromagnetic fields of the SPs decrease exponentially as the distance $|z| \to \infty$.

To derive the dispersion equation which describes the SPs, two types of wave, TE and TM waves, must be taken into account. This is due to the presence of the surface current at the interface $z = 0$, which mixes TE and TM waves [9].

Assuming that the electromagnetic waves propagate along the x-axis, we present the components of the electromagnetic field of the non-radiative TM waves in each of the media, 1, 2, 3. We have

$$H_{y,1} = H_1 \exp[\mathrm{i}(kx - \omega t) - p_1(z - d)] \qquad z > d \tag{1a}$$

$$E_{x,1} = (\mathrm{i}cp_1/\omega\varepsilon_1)H_{y,1} \qquad z > d \tag{1b}$$

$$E_{z,1} = -(ck/\omega\varepsilon_1)H_{y,1} \qquad z > d \tag{1c}$$

$$H_{y,2} = [H_2^{(1)} \exp(p_2 z) + H_2^{(2)} \exp(-p_2 z)] \exp[\mathrm{i}(kx - \omega t)] \qquad 0 < z < d \tag{2a}$$

$$E_{x,2} = -(\mathrm{i}c/\omega\varepsilon_2)(\partial H_{y,2}/\partial z) \tag{2b}$$

$$E_{z,2} = -(ck/\omega\varepsilon_2)H_{y,2} \tag{2c}$$

$$H_{y,3} = H_3 \exp[\mathrm{i}(kx - \omega t) + p_3 z] \qquad z < 0 \tag{3a}$$

$$E_{x,3} = -(\mathrm{i}cp_3/\omega\varepsilon_3)H_{y,3} \tag{3b}$$

$$E_{z,3} = -(ck/\omega\varepsilon_3)H_{y,3} \tag{3c}$$

$$E_y = H_x = H_z = 0 \qquad p_i = \sqrt{k^2 - \frac{\omega^2}{c^2}\varepsilon_i} \qquad i = 1, 2, 3.$$

For the non-radiative waves, the in-plane component of the wave vector k and the frequency ω should satisfy the following conditions:

$$\mathrm{Re}\, p_i > 0 \qquad i = 1, 3. \tag{4}$$

The components of the electromagnetic field for the non-radiative TE waves have the form

$$E_{y,1} = E_1 \exp[\mathrm{i}(kx - \omega t) - p_1(z - d)] \qquad z > d \tag{5a}$$

$$H_{x,1} = -\mathrm{i}(cp_1/\omega)E_{y,1} \tag{5b}$$

$$H_{z,1} = (ck/\omega)E_{y,1} \tag{5c}$$

$$E_{y,2} = [E_2^{(1)} \exp(p_2 z) + E_2^{(2)} \exp(-p_2 z)] \exp[\mathrm{i}(kx - \omega t)] \qquad 0 < z < d \tag{6a}$$

$$H_{x,2} = (\mathrm{i}c/\omega)(\partial E_{y,2}/\partial z) \tag{6b}$$

$$H_{z,2} = (ck/\omega)E_{y,2} \tag{6c}$$

$$E_{y,3} = E_3 \exp[\mathrm{i}(kx - \omega t) + p_3 z] \qquad z < 0 \tag{7a}$$

$$H_{x,3} = (\mathrm{i}cp_3/\omega)E_{y,3} \tag{7b}$$

$$H_{z,3} = (ck/\omega)E_{y,3} \tag{7c}$$

$$H_y = E_x = E_z = 0.$$

As the boundary conditions at the interface $z = d$, we use the conditions of the continuity of the tangential components of the electric and magnetic fields. The presence of a surface current at the interface $z = 0$ leads to discontinuity of the magnetic field tangential components:

$$H_{x,2}^{(s)} - H_{x,3}^{(s)} = \frac{4\pi}{c}(\sigma_{xx}E_y^{(s)} - \sigma_{xy}E_x^{(s)}) \tag{8a}$$

$$H_{y,2}^{(s)} - H_{y,3}^{(s)} = -\frac{4\pi}{c}(\sigma_{xx}E_x^{(s)} + \sigma_{xy}E_y^{(s)}). \tag{8b}$$

Here, the index s indicates the values of the electric and magnetic fields at the interface $z = 0$. The $\sigma_{ij}(\omega)$ are the 2DES conductivity tensor components. We assume that the spatial dispersion of the conductivity tensor can be neglected, i.e. $kl \ll 1$, where $l = (c\hbar/eB)^{1/2}$ is the magnetic length [5, 6]:

$$\sigma_{xx} = \frac{2e^2}{h}\frac{N\gamma}{1+\gamma^2} \tag{9a}$$

$$\sigma_{xy} = \frac{2e^2}{h}\frac{N}{1+\gamma^2}. \tag{9b}$$

In equations (9), $\gamma = (\nu - \mathrm{i}\omega)/\Omega$, where $\Omega = eB/mc$ is the cyclotron frequency; ν is the momentum relaxation frequency of the electrons; and $N = \pi l^2 n$ is the Landau-level filling factor which assumes integer values ($N = 1, 2, \ldots$) equal to the numbers of filled Landau levels lying below the Fermi level (n is the density of 2D electrons). Below, the effects of electron damping are ignored, which corresponds to the condition $\nu \ll \omega$.

Using the previously described boundary conditions at the interfaces $z = 0$ and $z = d$, we derive the dispersion equation which describes the propagation of the non-radiative SPs:

$$A_1A_2 + (4\pi\sigma_{xy}/c)^2 p_2p_3B_1B_2 = 0 \tag{10}$$

where

$$\begin{aligned} A_1 = {} & (p_3\varepsilon_2 - p_2\varepsilon_3 - (\mathrm{i}\,4\pi p_2p_3\sigma_{xx}/\omega))(p_2\varepsilon_1 - p_1\varepsilon_2) \\ & + \exp(2p_2d)(p_3\varepsilon_2 + p_2\varepsilon_3 + (\mathrm{i}\,4\pi p_2p_3\sigma_{xx}/\omega))(p_2\varepsilon_1 + p_1\varepsilon_2) \end{aligned} \tag{11}$$

$$\begin{aligned} A_2 = {} & (p_2 - p_3 + (\mathrm{i}\,4\pi\omega\sigma_{xx}/c^2))(p_2 - p_1) \\ & - \exp(2p_2d)(p_2 + p_3 - (\mathrm{i}\,4\pi\omega\sigma_{xx}/c^2))(p_2 + p_1) \end{aligned} \tag{12}$$

$$B_1 = p_2 - p_1 + \exp(2p_2d)(p_2 + p_1) \tag{13}$$

$$B_2 = p_2\varepsilon_1 - p_1\varepsilon_2 - \exp(2p_2d)(p_1\varepsilon_2 + p_2\varepsilon_1). \tag{14}$$

Under the conditions $\varepsilon_3 = \varepsilon_2$ and $d = \infty$, the dispersion equation (10) coincides with one derived for the SPs in the 2DES embedded in the dielectric medium with the dielectric constant ε_2 [5, 6]. In this case, the dispersion curves of the SPs in the vicinity of the CR ($\omega \approx \Omega$) intersect at the point $k_a \approx \sqrt{2\varepsilon_2}\Omega/c$. The group velocity of the SPs is $v_{ga} = 2\sqrt{2}c\alpha N/\varepsilon_2$. One can see that when changing N, the group velocity of the SPs is quantized into fundamental steps defined by α and the value of ε_2 [5].

If $\varepsilon_3 > \varepsilon_2$ and $d = \infty$, then the SPs propagate along a 2DES which is located at the interface of the semi-infinite media 2 and 3. In this case, the dispersion equation (10) reduces to

$$(p_3\varepsilon_2 + p_2\varepsilon_3 + (\mathrm{i}\,4\pi p_2p_3\sigma_{xx}/\omega))(p_2 + p_3 - (\mathrm{i}\,4\pi\omega\sigma_{xx}/c^2)) + (4\pi\sigma_{xy}/c)^2 p_2p_3 = 0. \tag{15}$$

It follows from equation (15) that the dispersion curves of the SPs in the vicinity of the CR intersect at the point

$$k_\infty \approx (\Omega/c)\left[(2/3)(\varepsilon_2 + \varepsilon_3 + \sqrt{(\varepsilon_3 - \varepsilon_2)^2 + \varepsilon_2\varepsilon_3})\right]^{1/2}. \tag{16}$$

The group velocity of the SPs at this point is equal to

$$v_{g\infty} = \frac{4\alpha N k_\infty \Omega^4 \sqrt{(\varepsilon_3 - \varepsilon_2)^2 + \varepsilon_2\varepsilon_3}}{c^3 p_{2\infty}^2 p_{3\infty}^2 (p_{2\infty} + p_{3\infty})} \tag{17}$$

where

$$p_{2\infty}^2 = k_\infty^2 - \frac{\Omega^2}{c^2}\varepsilon_2 \tag{18}$$

$$p_{3\infty}^2 = k_\infty^2 - \frac{\Omega^2}{c^2}\varepsilon_3. \tag{19}$$

We make the definition $\Delta\varepsilon \equiv \varepsilon_3 - \varepsilon_2$. As ε_2 and ε_3 are slightly different, i.e. $\Delta\varepsilon \ll \varepsilon_3, \varepsilon_2$, we have from equations (16) and (17)

$$k_\infty \approx k_a\left(1 + \frac{\Delta\varepsilon}{4\varepsilon_2}\right) \tag{20}$$

$$v_{g\infty} \approx v_{ga}\left(1 - \frac{\Delta\varepsilon}{2\varepsilon_2}\right). \tag{21}$$

Thus, in the case in which the 2DES is located between the two semi-infinite media 2 and 3 (which satisfy the condition $\varepsilon_3 > \varepsilon_2$), the point of intersection of the dispersion curves shifts to larger values of k (in comparison with the results of the paper [5]), and the phase and the group velocities of the SPs decrease.

If $d = 0$ (imposing this condition has the result that one can neglect the thickness of medium 2, which is correct when $p_2 d \ll 1$), the SPs propagate along the 2DES which is located between the media 1 and 3. For $\varepsilon_3 \gg \varepsilon_1$, we have from equation (15) that the dispersion curves of the SPs intersect at the point

$$k_0 \approx 2\sqrt{\frac{\varepsilon_3}{3}}\frac{\Omega}{c} = \sqrt{\frac{2\varepsilon_3}{3\varepsilon_2}}k_a. \tag{22}$$

In this case, the SPs have the group velocity

$$v_{g0} \approx \frac{6c\alpha N}{\varepsilon_3} = \frac{3}{\sqrt{2}}\frac{\varepsilon_2}{\varepsilon_3}v_{ga}. \tag{23}$$

If the values of ε_2 and ε_3 are only slightly different, we have $k_0 < k_\infty$ and $v_{g\infty} < v_{g0}$. Thus, for an arbitrary value of the thickness, d, the point of intersection of the dispersion curves in the vicinity of the CR is located in the interval $[k_0, k_\infty]$, and the group velocity of the SPs is located in the interval $[v_{g\infty}, v_{g0}]$.

3. Numerical results

It is convenient to introduce the dimensionless frequency $\xi = \omega/\Omega$, the dimensionless wave vector $\zeta = ck/\Omega$, and the dimensionless thickness $\delta = d\Omega/c$. First, we consider the limiting cases in which the 2DES is located between the two semi-infinite media, i.e. when $\delta = \infty$ and $\delta = 0$. In figure 2, the dispersion curves $\xi(\zeta)$ for SPs are shown for two cases: $\delta = \infty$ (solid lines) and $\delta = 0$ (dashed lines). The following parameters were chosen: $\varepsilon_1 = 1$, $\varepsilon_2 = 12$, and $\varepsilon_3 = 12.9$. The numbers 1 and 5 indicate the values of N considered. Dotted lines correspond to the light lines for the media 2 and 3. For comparison, in figure 2 the dispersion curves (chain lines) for the case considered in [5] ($\varepsilon_3 = \varepsilon_2 = 12$, $\delta = \infty$) are plotted. One can see from figure 2 that the point at which dispersion curves intersect, $\zeta_\infty = ck_\infty/\Omega$, for the case where $\delta = \infty$, is located to the right of the one obtained in

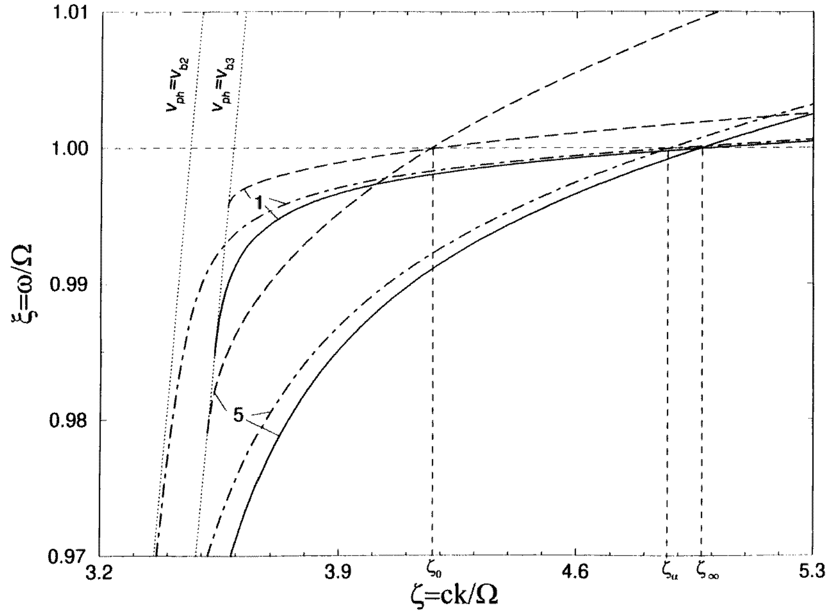

Figure 2. The dispersion curves for the SPs in the GaAs/Al$_x$Ga$_{1-x}$As heterojunction ($\varepsilon_1 = 1$, $\varepsilon_2 = 12$, $\varepsilon_3 = 12.9$) in the limiting cases where $\delta = \infty$ (solid lines) and $\delta = 0$ (dashed lines), for $N = 1$ and $N = 5$. The chain lines represent the dispersion curves for the SPs for the case considered in [5] ($\varepsilon_3 = \varepsilon_2 = 12$, $\delta = \infty$).

[5] ($\zeta_a = ck_a/\Omega$). This means that in the case where $\delta = \infty$, the larger value of the dielectric constant of the GaAs substrate (in comparison with the dielectric constant of the Al$_x$Ga$_{1-x}$As layer) leads to a decrease of the phase and the group velocities of the SPs in the vicinity of the CR. If δ decreases, the phase and the group velocities of the SPs increase, and they reach maximum values at $\delta = 0$. In this case, the point at which the dispersion curves intersect is indicated as $\zeta_0 = ck_0/\Omega$.

One can see from figure 2 that the difference between the dielectric constants of two media, 2 and 3, leads to an interesting new result. Namely, all dispersion curves start at the light line for the GaAs medium: $v_{ph} = v_{b3} = c/\sqrt{\varepsilon_3}$. Thus, the SPs have a low-frequency non-propagating region. For the case where $\delta = \infty$, the upper value of the frequency (ξ_s) for this region is

$$\xi_s = \sqrt{1 + \frac{4\alpha^2 N^2}{\varepsilon_3 - \varepsilon_2}} - \frac{2\alpha N}{\sqrt{\varepsilon_3 - \varepsilon_2}}. \tag{24}$$

For the case where $\delta = 0$, the upper value of the frequency (ξ_s) is determined by equation (24) in which the substitution $\varepsilon_2 \to \varepsilon_1$ should be made. When increasing the magnitude of the magnetic field $\boldsymbol{B}$ (or decreasing the value of N), the value of ξ_s increases in a step-like manner.

Now we consider the case in which $\varepsilon_1 = 1$, $\varepsilon_3 = \varepsilon_2 = 12$, and δ has a finite value. For this case, the spectrum of the SPs is shown in figure 3, for $N = 1, 5, 10$, and $\delta = 1.0$ (dashed lines) and $\delta = 0.1$ (solid lines). One can see that the finite value of the thickness, δ, of the Al$_x$Ga$_{1-x}$As layer (medium 2) leads to the following important properties. All dispersion curves in the vicinity of the CR ($\xi \approx 1$) intersect approximately at one point. In figure 3, this point of intersection is indicated as $\zeta_{0.1}$ for $\delta = 0.1$, and $\zeta_{1.0}$ for $\delta = 1$. One

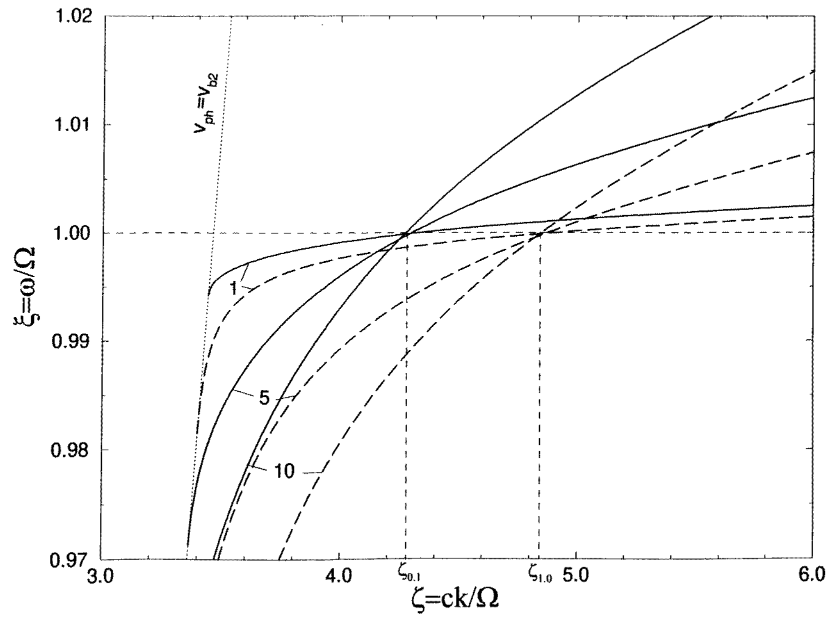

Figure 3. The dispersion curves for the SPs in the GaAs/Al$_x$Ga$_{1-x}$As heterojunction in the case in which $\varepsilon_2 = \varepsilon_3 = 12.0$, and for the finite values of the dimensionless thickness δ of the Al$_x$Ga$_{1-x}$As layer $\delta = 1.0$ (dashed lines) and $\delta = 0.1$ (solid lines), and for three values of N, $N = 1$, $N = 5$, and $N = 10$.

can see from figure 3 that when δ increases, the point of intersection of the dispersion curves shifts to the region of the lower values of ζ. In the vicinity of the CR, the group velocity of the SPs, $v_g = c(\partial\xi/\partial\zeta)$, exhibits fundamental steps (with changing N) depending not only on the fine-structure constant α, but also on the value of δ. When δ decreases, the group velocity of the SPs (the slope of the dispersion curves) increases. All dispersion curves start at the light line for the GaAs medium, on which the phase velocity of the SPs is equal to the velocity of the bulk electromagnetic waves in medium 3: $v_{ph} = v_{b3} = v_{b2} = c/\sqrt{\varepsilon_2}$ ($p_3 = p_2 = 0$ or $\xi = \zeta/\sqrt{\varepsilon_2}$). This means that the SPs have a low-frequency non-propagation region. The upper value for the frequency of this region depends on the value of δ. This non-propagation region extends from the origin to the frequency $\xi_s < 1$, which is determined by the following equation:

$$\xi_s = \frac{\sqrt{1 + 4\alpha N\delta + 4\alpha^2 N^2/(\varepsilon_2 - \varepsilon_1)} - 2\alpha N/\sqrt{\varepsilon_2 - \varepsilon_1}}{1 + 4\alpha N\delta}. \tag{25}$$

As the magnitude of the magnetic field increases, the value of ξ_s increases in a stepwise manner.

Now let us consider the change in the SP spectrum on the assumption that media 2 and 3 have greater dielectric constants. Let them be equal to the value of the dielectric constant of the GaAs substrate; i.e. we will consider $\varepsilon_3 = \varepsilon_2 = 12.9$. The SP spectrum for this case is shown in figure 4; the values of N and δ are the same as for figure 3. We can see that in the case where $\varepsilon_3 = \varepsilon_2 = 12.9$, all of the dispersion curves, together with their point of intersection, shift to the region of the larger values of ζ, and the slope of the dispersion curves decreases. The shift of the point of intersection of the dispersion curves to the region of the larger values of ζ has the result that the group and the phase velocities of the SPs in

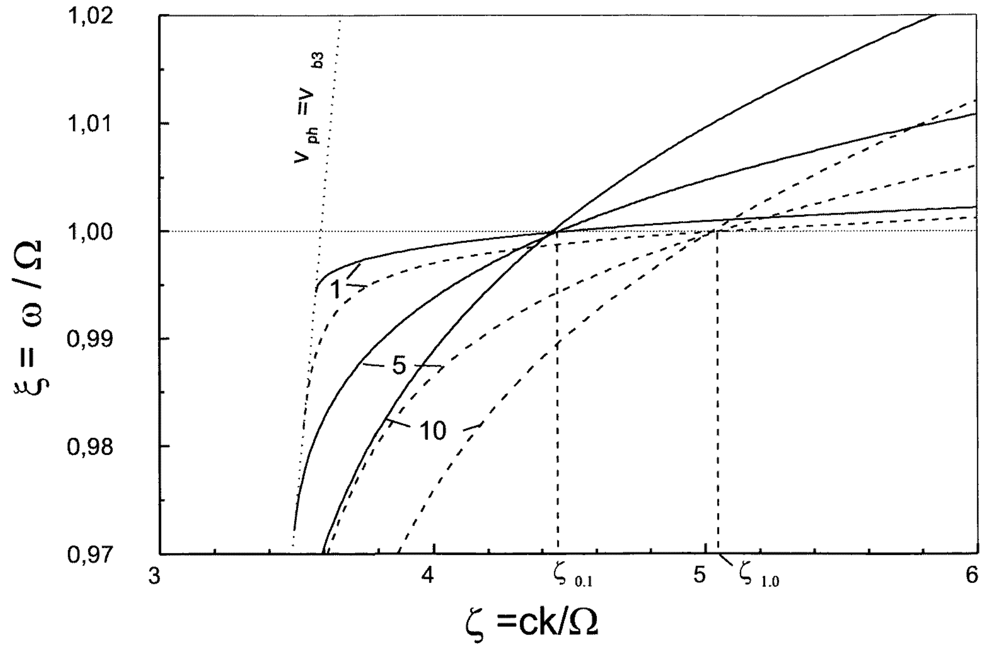

Figure 4. The dispersion curves for the SPs in the GaAs/$Al_xGa_{1-x}As$ heterojunction in the case in which $\varepsilon_2 = \varepsilon_3 = 12.9$, and for the finite values of the dimensionless thickness δ of the $Al_xGa_{1-x}As$ layer $\delta = 1.0$ (dashed lines) and $\delta = 0.1$ (solid lines), and for three values of N, $N = 1$, $N = 5$, and $N = 10$.

the case in which $\varepsilon_3 = \varepsilon_2 = 12.9$ are less than those in the case in which $\varepsilon_3 = \varepsilon_2 = 12.0$. Also, the size of the low-frequency non-propagation region of the SPs in the case in which $\varepsilon_3 = \varepsilon_2 = 12.9$ is larger than in the case in which $\varepsilon_3 = \varepsilon_2 = 12.0$.

Consider now the case in which medium 2 has a finite thickness, d, and $\varepsilon_3 > \varepsilon_2$. We assume that $\varepsilon_2 = 12.0$ (the $Al_xGa_{1-x}As$ layer) and $\varepsilon_3 = 12.9$ (the GaAs substrate). In this case, the spectrum of the SPs is shown in figure 5, for $N = 1, 5, 10$, and $\delta = 1.0$ (dashed lines) and $\delta = 0.1$ (solid lines). One can see that the dispersion curves take an intermediate position between those for the cases where $\varepsilon_3 = \varepsilon_2 = 12.0$ (figure 3) and $\varepsilon_3 = \varepsilon_2 = 12.9$ (figure 4). For $\delta = 0.1$ the point of intersection of the dispersion curves, $\zeta_{0.1}$, shifts slightly to the region of the lower values of ζ, in comparison to the case where $\varepsilon_3 = \varepsilon_2 = 12.9$. If $\delta = 1.0$ the point of intersection of the dispersion curves, $\zeta_{1.0}$, shifts considerably to the region of the lower values of ζ, and it lies approximately in the middle between the points of intersection of the dispersion curves for the cases where $\varepsilon_3 = \varepsilon_2 = 12.0$ and $\varepsilon_3 = \varepsilon_2 = 12.9$. The upper boundary of the low-frequency non-propagation region of the SPs, ξ_s, satisfies the following equation:

$$\tanh(\xi\delta\sqrt{\varepsilon_3 - \varepsilon_2}) = \sqrt{\varepsilon_3 - \varepsilon_2}\,\frac{4\alpha N\xi - \sqrt{\varepsilon_3 - \varepsilon_1}(1 - \xi^2)}{(1 - \xi^2)(\varepsilon_3 - \varepsilon_2) - 4\alpha N\xi\sqrt{\varepsilon_3 - \varepsilon_1}}. \qquad (26)$$

In the case that we are considering ($\varepsilon_2 = 12.0$, $\varepsilon_3 = 12.9$), the low-frequency non-propagation region of the SPs is larger than those in the cases where $\varepsilon_3 = \varepsilon_2 = 12.0$ and $\varepsilon_3 = \varepsilon_2 = 12.9$. This region expands with the decrease of δ.

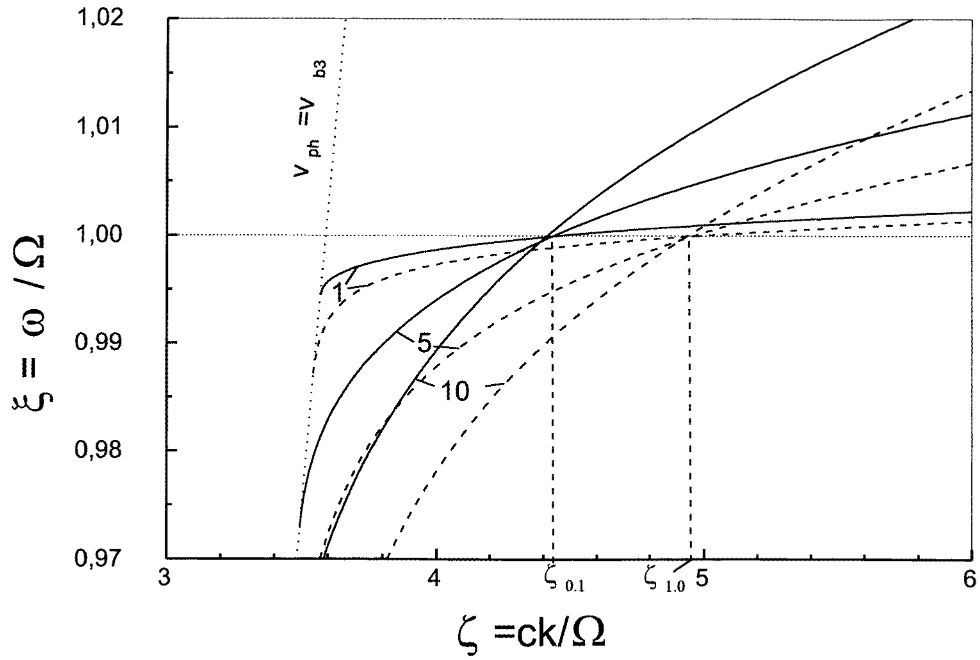

Figure 5. The dispersion curves for the SPs in the GaAs/Al$_x$Ga$_{1-x}$As heterojunction in the case where $\varepsilon_2 = 12.0$, $\varepsilon_3 = 12.9$, and for the finite values of the dimensionless thickness δ of the Al$_x$Ga$_{1-x}$As layer $\delta = 1.0$ (dashed lines) and $\delta = 0.1$ (solid lines), and for three values of N, $N = 1$, $N = 5$, and $N = 10$.

4. Conclusion

In conclusion, we have calculated the spectrum of the SPs in the GaAs/Al$_x$Ga$_{1-x}$As heterojunction in a high magnetic field, i.e. for a case in which the effects of quantization of the conductivity tensor of a 2DES are crucial. It is shown that all of the dispersion characteristics of the SPs under the conditions of the integer quantum Hall effect are quantized. In the vicinity of the cyclotron resonance, the phase and the group velocities of the SPs decrease significantly. The SP group velocity exhibits a stepwise behaviour. The magnitude of these steps is determined by the fine-structure constant $\alpha = e^2/\hbar c$, the thickness, d, of the Al$_x$Ga$_{1-x}$As layer, and the values of the dielectric constants of GaAS and Al$_x$Ga$_{1-x}$As.

The values of the phase and the group velocities of the SPs can significantly decrease with increasing thickness d of the Al$_x$Ga$_{1-x}$As layer, and with increasing difference between the dielectric constants of GaAs and Al$_x$Ga$_{1-x}$As. This fact can be used in various applications in microelectronics and in making contactless measurements of the parameters of the GaAs/Al$_x$Ga$_{1-x}$As heterojunction.

Recent experiments using inelastic light scattering [10–13] and far-infrared transmission spectroscopy [14, 15] have observed collective excitations in a 2DES in a high magnetic field. In these experiments one can study the SP dispersion curves with in-plane wave vectors $k \geqslant 2 \times 10^5$ cm^{-1}. For such values of k, the phase velocity of the SPs in the magnetic field $B = 5$ T (which corresponds to $N = 1$) in the vicinity of the CR, $\omega \approx \Omega \approx 10^{13} c^{-1}$, is $v_{ph} \leqslant 0.01c$. Investigations of the SPs using inelastic light scattering are of significant interest for measuring the Landau-level filling factor dependence using dispersion data with no direct contact with the GaAs/Al$_x$Ga$_{1-x}$As heterojunction.

Acknowledgments

We are grateful to G D Doolen for useful discussion. NNB is grateful to the Theoretical Division and the Center for Nonlinear Studies of the Los Alamos National Laboratory for hospitality during the completion of this work. This research was supported in part by the Linkage Grant 93-1602 from the NATO Special Programme Panel on Nanotechnology. The work at Los Alamos was supported by the US DoE.

References

[1] Agranovich V M and Mills D L (ed) 1982 *Surface Polaritons. Electromagnetic Waves at Surfaces and Interfaces* (Amsterdam: North-Holland)
[2] Boardman A D (ed) 1982 *Electromagnetic Surface Modes* (New York: Wiley)
[3] Ando T, Fowler B and Stern F 1982 *Rev. Mod. Phys.* **54** 437
[4] Kosevich Yu A, Kosevich A M and Granada J C 1988 *Phys. Lett.* **127A** 52
[5] Aronov I E and Beletskii N N 1996 *J. Phys.: Condens. Matter* **8** 4919
[6] Aronov I E, Beletskii N N, Berman G P and Bishop A R 1997 *Phys. Rev.* B **56** 10 392
[7] Constantinou N C and Cottam M G 1986 *J. Phys.: Condens. Matter* **19** 739
[8] Wallis R F and Quinn J J 1988 *Phys. Rev.* B **38** 4205
[9] Nakayama M 1974 *J. Phys. Soc. Japan* **36** 393
[10] Sohn L L, Pinczuk A, Dennis B S, Pfeiffer L N and West K W 1995 *Solid State Commun.* **93** 897
[11] Pinczuk A 1977 *Perspectives in Quantum Hall Effect* ed S Das Sarma and A Pinczuk (New York: Wiley) p 307
[12] Burstein E, Pinczuk A and Buchner S 1979 *Physics of Semiconductors (IOP Conf. Proc. 43)* ed B L Wilson (Bristol: Institute of Physics Publishing) p 1231
[13] Pinczuk A and Abstreiter G 1989 *Springer Topics in Applied Physics* vol 66 (Berlin: Springer) p 153
[14] Batke E, Heitmann D, Kotthaus J P and Ploog K 1985 *Phys. Rev. Lett.* **54** 2367
[15] Batke E, Heitmann D and Tu S W 1986 *Phys. Rev.* **34** 6951