Local Magnetoplasmon Modes of a Semiconductor Superlattice with Broken Translational Symmetry

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We investigate the local collective modes arising in a semiconductor superlattice with a defect two-dimensional (2D) electron layer in the presence of an external static transversal magnetic field. The dispersion relation of the local mode is derived. We investigate the homogeneous (along the electron planes) low-frequency local modes considering retarded effects. It is shown that in the retarded region of the spectrum there exists local magnetoplasmon modes which have frequencies much lower than the electron cyclotron frequency of the 2D carriers.

Extensive work has been devoted to the theoretical and experimental study of the properties of low-dimensional heterostructures (see e.g.[1]). In particular, the study of the collective excitations arising in such structures has attracted the attention of many researchers[2,3]. Most of the theoretical work in this field is concerned with infinite and semi-infinite[5−6] superlattices. In a series of papers Bloss considered plasmon modes of an inflnite periodic array of quantum wells, where all the wells are doped with the same electron density except for one, doped with a different surface concentration. It was shown, that a local plasmon mode arises due to the breaking of translational syrnmetry along the superlattice axis. In the present communication we investigate the local collective modes which arise in a semiconductor superlattice with a defect two-dimensional electron layer when an external static magnetic field is apphed along the superlattice axis (i.e., perpendicular to the electron layer planes).

We consider a model, consisting of a one-dimensional infinite array of quantum wells with periodicity d. The z-direction is taken along the superlattice axis. We assume that all the quantum wells are uniformly doped with a surface density η_0, except for the quantum well at $z = 0$, which is doped with a surface density of carriers η_d. An external static magnetic field B_0 is applied along the z direction. The wells are so apart, that we can neglect wave function overlap. Therefore, the quantum wells are coupled only by the electromagnetic interaction associated with the dynamics of the electron system. In order to describe the collective excitations, we must solve Maxwell's equations for the induced fields at the j-th layer and take into account the standard boundary conditions. To solve for the local modes in the superlattice with the defect electron layer, we assume a decaying solution

$$E^{\pm}_{\delta,j} = E^{\pm}_{\delta,0} e^{-\alpha d} \ , \quad (\delta = x, y) \ , \tag{1}$$

where α is a parameter characterizing the attenuation of the fields along the superlattice axis. We obtain the following relation.

$$\left[\frac{\kappa d}{2} S(\kappa,\alpha) - \frac{\omega^2 - \omega_H^2}{\omega_{pl}^2}\right] \left[\frac{\omega^2 d\epsilon}{2c^2\kappa} S(\kappa,\alpha) + \frac{\omega^2 - \omega_H^2}{\omega_{pl}^2}\right] = \left[\frac{\omega_H d\sqrt{\epsilon}}{2c} S(\kappa,\alpha)\right]^2 \tag{2}$$

Here $\omega_{pl} = \sqrt{4\pi e^2\eta_0/(m\epsilon d)}$ is the three-dimensional plasmon frequency, $S(\kappa,\alpha)$ is the superlattice structure factor $S(\kappa,\alpha) = sinh(\kappa d)/(cosh(\kappa d) - cosh(\alpha d))$, κ is related to the in-plane wave number k and the excitation frequency ω by $\kappa = \sqrt{k^2 - \omega^2\epsilon/c^2}$ and ω_H is the electron cyclotron frequency of the 2D carriers.

The local magnetoplasmon mode, associated with the broken translational symmetry of the model considered here, must lie outside the bulk magnetoplasmon band. In order to describe this mode, it is necessary to consider the boundary conditions at the defect layer $(z = 0)$. We have

$$\left[\frac{\kappa d}{2}\eta S'(\kappa,\alpha) + \frac{\omega^2 - \omega_H^2}{\omega_{pl}^2}\right]\left[\frac{\omega^2 d\epsilon}{2c^2\kappa}\eta S'(\kappa,\alpha) - \frac{\omega^2 - \omega_H^2}{\omega_{pl}^2}\right] = \left[\frac{\omega_H d\sqrt{\epsilon}}{2c}\eta S'(\kappa,\alpha)\right]^2 \tag{3}$$

where $S'(\kappa,\alpha) = sinh(\kappa d)/(\exp(\kappa d) - cosh(\kappa d))$ and $\eta = \eta_d/\eta_0$.

Relations (2,3) permit us to obtain x and ω. They can be solved analytically in some important cases. Here we shall consider the homogeneous $(k = 0)$ oscillations in the retarded region. In this case the relations (2-3) transform into

$$x \equiv e^{\alpha d} = \left(1 - \eta^{-1}\right) cos\left(\frac{\omega d\sqrt{\epsilon}}{c}\right) + \Delta(\eta)\sqrt{\left(1 - \eta^{-1}\right)^2 cos^2\left(\frac{\omega d\sqrt{\epsilon}}{c}\right) - \left(1 - 2\eta^{-1}\right)} \tag{4}$$

$$\omega = \pm\omega_H + \frac{\omega_p^2 d\sqrt{\epsilon}}{2c}\left[cot\left(\frac{\omega d\sqrt{\epsilon}}{c}\right) + \Delta(\eta)\sqrt{cot^2\left(\frac{\omega d\sqrt{\epsilon}}{c}\right) - \eta(\eta - 2)}\right] \tag{5}$$

Here we have introduced the function $\Delta(\eta) = \theta(\eta - 1) - \theta(1 - \eta)$, where $\theta(x)$ is the Heaviside step function. We see that the magnitude $x = e^{ad}$ shows a dependence on the external magnetic field. This follows from the fact that the modes described by (5) are due to the retarded effects.

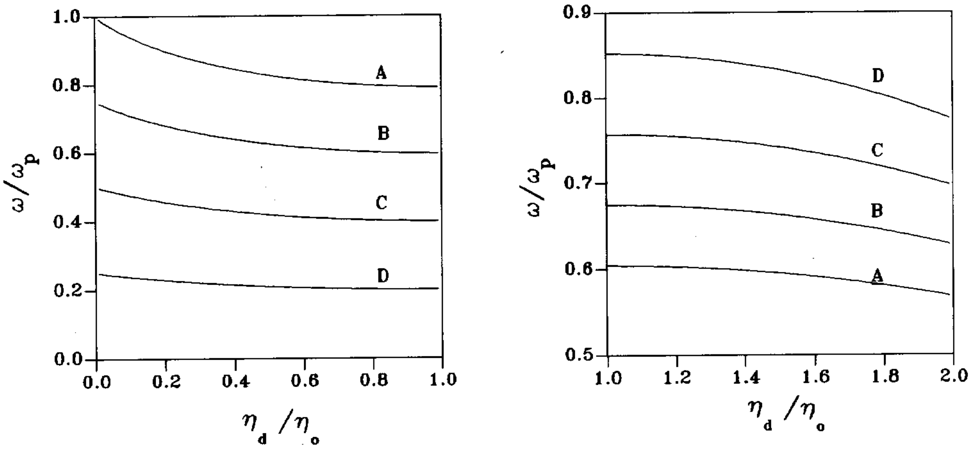
In the particular case when $|1 - \eta| \ll 1$ we find localized modes with frequencies close to the center or the edge of the Brillouin mini-zone. We obtain for these frequencies the relation

$$\omega = \omega_* - \Delta(\eta)(1 - \eta)^2\frac{\omega_{pl}^2}{4c\sqrt{\epsilon}}\sin\left(\frac{\omega_* d}{c\sqrt{\epsilon}}\right) \tag{6}$$

where ω_* is the frequency at which the local mode enters the bulk band of the magnetoplasmon oscillations of the wave-guided type existing in the ideal system[7]. For the parameter relation $\omega_H > c/d\sqrt{\epsilon}$ the frequency ω_* satisfies the inequality $\omega_* < \omega_H$. This means, that the local modes have frequencies lower than the electron cyclotron frequency. The above features are illustrated in Fig. 1, where we have plotted the dependence $\omega = \omega(\eta_d)$ for different values of the applied external magnetic field.

Fig. (1a) displays the dependence $\omega = \omega(\eta_d)$ for the case $\eta_d < \eta_0$. When η_d tends to zero, the local frequency approaches the cyclotron frequency. This means that the absence of carriers at the defect layer leads to the appearance of a local mode with a frequency equal to the cyclotron frequency of the carriers at the remaining layers. We see also that for a fixed value of the surface density of carriers η_d in the defect layer, the local frequency increases with the applied magnetic field. On the other hand, for a given value of the external applied magnetic field B_0, ω decreases with the increasing of η_d. Fig. (1b) displays the dependence $\omega = \omega(\eta_d)$ for the case $\eta_d > \eta_0$. As in the previous case, for a given value of the external applied magnetic field B_0 the frequency ω is a decreasing function of the surface density of carriers η_d. But, for a fixed value of η_d, the local frequency decreases with the applied magnetic field.

Thus, we conclude that the account of the retarded effects on the collective excitation magnetoplasmon



1(a) 1(b)

Figure 1. Plot of the homogeneous ($k = 0$) low-lying local magnetoplasmon frequency vs the surface density of carriers at the defect layer for $\eta_d < \eta_0$ and for different values of the cyclotron frequency: We have chosen the parameter relation $\omega_{pl} d\epsilon^{1/2}/c = 1$; (A) $\omega_H = \omega_{pl}$, (B) 0.75 ω_{pl}, (C) 0.5 ω_{pl}, (D) 0.25 ω_{pl}.

spectrum of the model considered here, leads to the appearance of a localized mode whose frequency hes below the electron cyclotron frequency.

Although there are so far no experimental results on superlattices with a single defect layer, we consider that the local modes described here must be detected with the aid of scattering experiments. In this case it is necessary to have a complete theory of the scattering experiment in order to predict the spectral width, the line shape and the integrated density associated to scattering from these local modes.

Acknowledgments

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