Plasmons in weakly disordered array of quantum wires

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Abstract

The paper deals with the theoretical investigation of intrasubband plasmons in weakly disordered array of quantum wires (QWs), consisting of finite number of QWs. The array of QWs is characterized by the fact that the density of electrons of one "defect" QW was different from that of other QWs. It is shown that the amount of plasmon modes in weakly disordered array of QWs is equal to the number of QWs in array. The existence of the local plasmon mode, whose properties differ from those of usual modes, is found. We point out that the local plasmon mode spectrum is slightly sensitive to the position of "defect" QW in array. At the same time the spectrum of usual plasmon modes is shown to be very sensitive to the position of "defect" QW.

Key words: quantum wire; plasmons

1. Introduction

Quasi one-dimensional electron systems (1DES) or quantum wires (QWs) are artificial structures in which the motion of charge carriers is confined in two transverse directions but is essentially free (in the effective mass sense) in the longitudinal direction. Collective charge-density excitations, or plasmons in QWs are the objects of great physicist's interest due to some new unusual dispersion properties. Firstly, the plasmon spectrum depends strongly on the width of QW [1]. Secondly, 1D plasmons are free from the Landau damping [2] in the whole range of wavevectors.

From the point of view of practical application so-called weakly disordered arrays of low-dimensional systems, containing some defect, are the objects of interest. Recently the plasmons in weakly disordered superlattice, formed of an finite number of equally spaced two-dimensional electron systems (2DES), were theoretically investigated [3].

This paper deals with the theoretical investigation of plasmons in finite weakly disordered array of QWs, consisting of a finite number M of QW, arranged at planes $z = ld$ ($l = 0, ..., M-1$ is the number of QW, d is the distance between adjacent QWs). We suppose that all QWs possess equal 1D density of electrons N except one "defect" QW whose density of electrons is equal to N_{d}. So, the density of electrons in l-th QW can be expressed as $N_l = (N_{\mathrm{d}} - N)\delta_{pl} + N$. Here p is the number of "defect" QW arranged at the plane $z = pd$, δ_{pl} is the Cronecker delta. QWs are considered to be placed into the uniform dielectric medium with dielectric constant ε. We consider the movement of electrons to be free in x-direction and is considerably confined in directions y and z. At the same time we suppose that the width of all QWs is equal to a in y-direction and is equal to zero in z-direction.

2. Dispersion relation and numerical results

To obtain the collective excitations spectrum we start with a standard linear-response theory in an random phase approximation. Also we take into account only the lowest subband in each QW. The dispersion relation for intrasubband plasmons can be represented in the final form as

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$$\det|\delta_{l,l'} - \Pi^{l'} U_{l,l'}| = 0, \tag{1}$$

where

$$U_{l,l'} = \frac{8e^2}{\varepsilon a^2} \int\limits_{-a/2}^{a/2} \mathrm{d}y' \int\limits_{-a/2}^{a/2} \mathrm{d}y\, K_0(q_x \zeta)\, \cos^2\left(\frac{\pi y}{a}\right) \times$$
$$\times \cos^2\left(\frac{\pi y'}{a}\right),$$

$\zeta = [(y-y')^2 + (l-l')^2 d^2]^{1/2}$, $K_0(x)$ is the zeroth-order modified Bessel function of the second kind, $\Pi^{l'}$ is the noninteracting 1D polarizability (”bare bubble”) function, which at zero temperature and in the long-wavelength limit (where $q_x \to 0$) can be written as $\Pi^l = \dfrac{N_l}{m^*}\dfrac{q_x^2}{\omega^2}$.

Now we consider the dependence of plasmon spectrum upon the value of 1D electron density in ”defect” QW. Fig.1 presents the dependence of plasmon dimensionless frequency ω/ω_0 ($\omega_0^2 = 2Ne^2/\varepsilon m^* a^2$ is the plasma frequency) upon the ratio N_d/N for different positions of the ”defect” QW in the array. As seen from fig.1, the intrasubband plasmon spectrum in finite array of QWs contains M modes. So, the number of modes in the spectrum is equal to the number of QWs in the array. At the same time the propagation of plasmons in weakly disordered array of QWs is characterized by the presence of local plasmon mode (LPM). As seen from fig.1, the frequency of LPM increases when the value of ratio N_d/N is increased. Also from the comparison of fig.1a,b,c it follows, that the LPM spectrum depends weakly upon the position of ”defect” QW in array. However, the spectrum of usual plasmon modes is more sensitive to the position of ”defect” QW in the array. At the same time the usual plasmon modes spectrum is characterized by such a features. As $p = 0$ (fig.1a) when the value of ratio N_d/N is increased, the frequency of all usual plasmon modes also increases. However when $p = 1$ (figure 1b) the frequency of one of the usual plasmon modes (curve 2) does not practically depend upon the value of ratio N_d/N. In the case where $p = 2$ (figure 1c) there are already two plasmon modes (curves 1 and 3) which possess such a particularity.

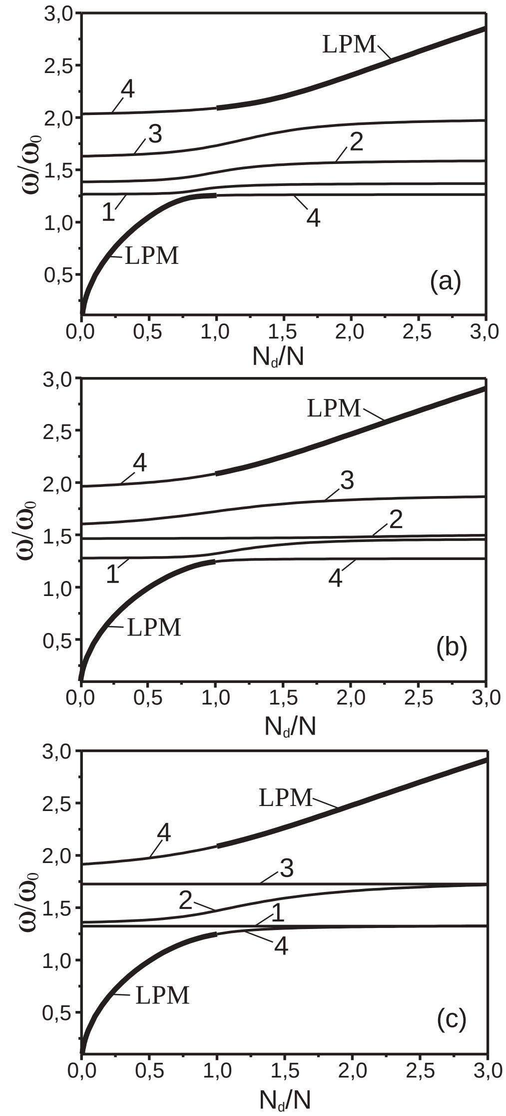

Fig. 1. Dependence of plasmon frequency upon the ratio N_d/N in the case where $M = 5$, $d = 15a^*$, $a = 20a^*$, $q_x a^* = 0{,}04$ ($a^* = \varepsilon\hbar^2/m^* e^2$ is the effective Bohr radius) and for three cases of ”defect” QW position in the array: (a) $p = 0$, (b) $p = 1$, (c) $p = 2$.

3. Conclusion

In conclusion, we calculated the plasmon spectrum of finite weakly disordered array of QWs, which contains one ”defect” QW. It should be emphasized, that the above-mentioned features of plasmon spectra can be used for diagnostics of defects in QW structures. So, the properties of LPM can be used for the determination of the electron density in the ”defect” QW. At the same time the properties of usual plasmon modes can be used to define the position of the ”defect” QW in the array.

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