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PLASMA AND SINGLE PARTICLE EXCITATIONS IN QUASI-ONE-DIMENSIONAL ELECTRON SYSTEMS

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The equilibrium properties and dynamic response of quasi-one-dimensional electron systems (1DES) have been calculated for a confinement modelled by a harmonic oscillator potential. These calculations are compared with self-consistently calculated 1D subband separations in a split-gate configuration. It is shown that in the limit of a vanishing occupation the classical dynamic response frequency coincides with the subband separation. With increasing number of occupied 1D subbands the dynamic response frequency decreases slightly whereas the subband separation decreases drastically. Thus, for a large number of occupied 1D subbands, the dynamic response frequency is significantly higher than the 1D subband separation as is observed in experiments.

Quasi-one-dimensional electronic systems (1DES) are currently the subject of increasing interest (e.g. refs. [1–6]). Starting from 2DES, e.g. AlGaAs/GaAs heterostructures, where the electrons are confined in z-direction normal to the interface, these 1DES can be realized by an additional lateral confinement acting in x-direction. It is thereby possible to induce quantum confined discrete energy levels, E_x^i, and restrict the free motion of the electrons to the y-direction. From Shubnikov–de Haas (SdH) type of dc-experiments on those samples typical values of 1 to 3 meV for the separation of 1D subbands are found [1–5]. However, in far infrared (FIR) experiments on the same samples resonance excitations were observed at significantly higher energies. It was experimentally demonstrated that for currently investigated 1DES with many occupied subbands, the FIR response is strongly governed by collective effects and has the character of a local plasmon resonance (see ref. [6], also for additional references on FIR excitations in 1DES).

In this paper we calculate classically the equilibrium and dynamic properties of electrons bound in a single or in an array of harmonic oscillator potentials. We then discuss the influence of quantum confinement on the FIR response and compare with the 1D subband separation. This latter discussion in particular addresses AlGaAs/GaAs heterostructures with split-gate configuration as sketched in fig. 1 and heavily uses numerical results of self-consistent 1D subband calculations for these structures by Laux et al. [7].

We assume an external parabolic confining potential described by

$$V_{\text{conf}}(x) = \sum_l \frac{K}{2}(x - la)^2 + \text{const}, \tag{1}$$

where l is the index of the stripe, a is the periodicity and K is the curvature which characterises the parabolic potential. It has been shown by numerical calculations that this harmonic oscillator approach is actually very well fulfilled in a split-gate configuration at least up to four occupied subbands [7].

Let us first consider the equilibrium situation in

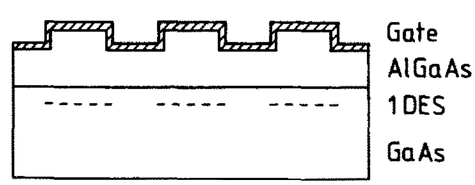

Fig. 1. Sketch of a periodic array of 1DES with free dispersion in y-direction which is induced via a split-gate configuration.

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the classical limit for an individual stripe ($l=0$ in (1)). We have

$$V_{\rm conf}(x)+e\phi(x)={\rm const}\,, \tag{2}$$

$$\phi(x)=\frac{e}{\kappa}\int_{-a_0}^{+a_0} n(s)\ln\frac{L}{|x-s|}\,{\rm d}s\,, \tag{3}$$

$$\int_{-a_0}^{+a_0} n(s)\,{\rm d}s=N_{\rm L}\,. \tag{4}$$

Here $\phi(x)$ is the electron potential, $n(x)$ the equilibrium electron density, κ the dielectric constant, $N_{\rm L}$ the linear electron density and L the geometrical size along the y-direction, $2a_0$ is the width of the electron channel.

The solution for this system of equations, (2)–(4), is

$$n(x)=n_0(1-x^2/a_0^2)^{1/2},\quad -a_0\le x\le a_0\,, \tag{5}$$

with

$$n_0=\kappa K a_0/(\pi e^2),\quad a_0^2=2e^2N_{\rm L}/K\kappa\,, \tag{6}$$

The eigenfrequency of the dipole plasmon mode in an individual stripe can be calculated, neglecting retardation, from the motion equation and the continuity equation:

$$-m^*\dot{v}=e\phi'(x,t)+V'_{\rm conf}(x)\,, \tag{7}$$

$$\dot{n}+\partial(n\cdot v)/\partial x=0\,, \tag{8}$$

where v is the electron velocity and m^* is the electron mass.

We can show that the ansatz

$$n(x,t)=n(x-\delta(t)),\quad \int_{-a_0+\delta(t)}^{+a_0+\delta(t)} n(x,t)\,{\rm d}x=N_{\rm L}\,, \tag{9}$$

$$v=\dot{\delta},\quad e\phi=e\phi(x-\delta(t))=-\tfrac{1}{2}K\cdot(x-\delta(t))^2+{\rm const}\,,$$

where $\delta(t)$ is the amplitude of the oscillation, satisfies self-consistently eq. (8). We then find from (7), (9) and (3) that the dipole plasma frequency is

$$\omega_{\rm p}^2=K/m^*\,. \tag{10}$$

Thus, in a parabolic confinement potential, the classical collective dipole mode frequency coincides with the individual motion. Note that the ansatz (9) is not at all trivial. This ansatz is valid only for a parabolic confinement and the lowest plasma modes. This ansatz will not solve (9) and (10) for potential of different shape or for the higher frequency modes.

In some experiments (e.g. refs. [2–6]) arrays of periodic stripes are investigated. In this case, taking into account the Coulomb interaction of neighbouring stripes, it follows from the equation of motion (for nearest neighbours)

$$-m^*\omega^2\delta_l=\tilde{K}\cdot\delta_l+\frac{eN_{\rm L}}{\kappa a}(\delta_{l+1}+\delta_{l-1}-2\delta_l)\,, \tag{11}$$

with

$$\tilde{K}=K+2eN_{\rm L}/\kappa a. \tag{12}$$

In this case we thus have a renormalisation of the dipole plasma mode frequency at $q=0$

$$\tilde{\omega}_{\rm p}^2=\tilde{K}/m^* \tag{13}$$

and the appearance of a positive dispersion ($(\partial\omega/\partial q>0)$, q is the wave vector perpendicular to the stripes)

$$m^*\omega_{\rm p}^2=\tilde{K}+4N_{\rm L}e^2\sin^2(qa/2)/(\kappa a^2)\,. \tag{14}$$

A similar dispersion has also been calculated in ref. [8]. Let us now discuss the quasi-classical regime. In this case eq. (2) should be generalized to

$$V_{\rm conf}(x)+e\phi(x)+E_{\rm F}(x)={\rm const},\quad E_{\rm F}=\frac{\pi\hbar^2}{m^*}n(x)\,. \tag{15}$$

Thus the combination $V_{\rm eff}(x)=V_{\rm conf}+e\phi(x)$ is not constant and gives rise to the quantisation of the individual electron motion, $V_{\rm eff}(x)={\rm const}-(\pi\hbar^2/m^*)n(x)$, where $n(x)$ is, in zero approximation, given in (5). It is evident that in the regime where the number of occupied subbands is large, the potential $V_{\rm eff}(x)$ is not parabolic and $V_{\rm eff}(x)\ll V_{\rm conf}(x)$. This behaviour is nicely demonstrated in self-consistent numerical calculations of the 1D subband structure for a split-gate configuration in ref. [7]. In fig. 2 we have depicted the linear density $N_{\rm L}$ and the separation $E_{i+1}-E_i$ of the lowest unoccupied subband, E_{i+1}, to the highest occupied subband, E_i, from the numerical results in the latter reference. At $V_{\rm g}=-1.53$ V, the onset for the filling of the lowest 1D subband, E_0, occurs. At $V_{\rm g}=-1.46$ V, (-1.41, -1.35,...) successively higher subbands are occupied. This occupation leads immediately to a strong decrease of the subband spac-

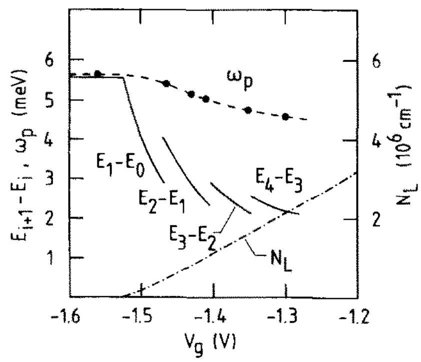

Fig. 2. Linear carrier density N_L (dash-dotted line) and 1D subband spacing $E_{i+1}-E_i$ (full lines) between the lowest unoccupied (E_{i+1}) and highest occupied (E_i) subband versus gate voltage V_g in a split-gate structure with 400 nm slits. The data are extracted from the self-consistent subband calculations of ref. [7]. Starting at $V_g=-1.53$ V, (-1.46, -1.41, -1.35, -1.3) the lowest (1st, 2nd,...) 1D subband is occupied. Full circles indicate plasma frequencies. The dashed line is extrapolated between the different calculated plasma frequencies.

ing, as shown for the highest subband in fig. 2. Lower-lying subbands have even slightly smaller separations.

We can now compare this subband separation with our calculated response frequencies. For $N_L \approx 0$ the calculated potential (fig. 2 of ref. [7]) is indeed in very good approximation parabolic. We can thus deduce the curvature and determine, via equations (6) and (10) the dipole plasma mode frequency which gives $\omega_p = 5.7$ meV. It agrees excellently with the subband spacing for $V_g < -1.53$ V in fig. 2. This directly visualizes our statement, that, for small N_L, the plasma eigenfrequency and the subband separation coincide. From the electron distribution of fig. 4. in ref. [7] we see that already for four occupied 1D subbands the system behaves quasi-classically. On the other hand, from fig. 2 in ref. [7] we find that in the occupied regime the potential is still approximately parabolic. We can then use our approach to determine K via (6) from $N_L = 2.2 \times 10^6$ cm^{-1} and $a_0 = 51$ nm at $V_g = -1.3$ V and find $\omega_p = 4.6$ meV. This frequency, which is depicted in fig. 2 by a full circle at $V_g = -1.3$ V, is significantly larger than the subband spacing of 2.1 meV. Thus there is a significant difference of about a factor two in this regime between the subband spacing and the plasma–dipole mode. Similar values are also observed in experiments, e.g. refs. [4–6]. Fig. 2 also demonstrates the increase of the plasmon frequency with decreasing gate voltage as it has been observed experimentally for samples similar to the structures calculated in ref. [7] (refs. [2] and [4], and also in measurements by ourselves).

In conclusion, we have demonstrated that the dynamic response frequency of the dipole-plasmon mode in 1DES with many occupied 1D subbands is significantly larger than the single particle excitation. With decreasing occupation, this difference decreases, and, in the limit of an empty channel, the FIR frequency coincides with the one particle excitation.

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