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Quasi-One-Dimensional Electron Gas in a Gas Quantum Wire

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ABSTRACT

The semiconductor technology developed mainly from the second half of the twenty century allowed the fabrication of several electronic devices that helps in the monitoring and information about the economic activities that can impact the environment preservation. Therefore, here we study the semiconductors properties particularly the ultrthin quantum wires properties, due to it potential application in electronic devices fabrication. Particularly we have investigated the effects of the plasmon–(LO) phonon interaction on the intrasubband static structure factor and the plasmon energy associated with the lowest subband in GaAs-AlGaAs parabolic QWW as a function of the electronic densities. We observe the presence of oscillations in the static structure factor spectra and show that they are directly related to the resonant split of the intrasubband collective excitation energy.

Keywords: semiconductor, quantum wire, collective excitation energy.

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The technology developed from the manipulation of semiconductor materials and the manufacture of electronic devices led to the development of computers with large information storage capacity and ultra fast processing speed in addition to several types of sensors that contributed significantly to the monitoring of industrial pollution, in the control of deforestation, in the detection of forest fires, in the generation of clean and sustainable energy, etc. As an example, remote sensing of the earth's surface by satellites allows us to obtain data on hydrology, ecology, oceanography, glaciology, geology, as well as monitoring economic activities both in cities and in the countryside and their impact on the environment. The semiconductor device industry is also present in the monitoring of oil and gas refineries and terminals through the Air Pollution Geospatial Measurement System (GMAP), which assesses and detects possible air pollutants. In addition, the oceans are being monitored and protected by sensors that measure the oceanic pH level to determine the acidity of our oceans, which could wipe out entire ecosystems if they are not monitored and controlled. Otherwise photovoltaic systems based on semiconductor technology are used to convert solar energy into clean energy without CO2 emission and the development of light-emitting diode (LED) technology has enabled the development of energy-saving devices such as ordinary lamps that illuminate the streets and homes.

The semiconductors materials properties were established during the 1930's when the Bloch energy band theory was applied to the distinction between conductors, insulation and semiconductors. In the case of insulators and semiconductors, the last electron-occupied energy band (called the Valencia Band (BV)) is completely filled, so that the absence of unoccupied electronic states in this band does not favor the conduction of electric current. The electronic states unoccupied in these materials are located in bands called Conduction Bands (BC) that are energetically separated from the BV by a region devoid of allowed energetic states, known as a gap region. The separation between the valence band top (BV) and the conduction band bottom (BC) is known as gap energy. This gap energy is the key to the electronic properties of semiconductor materials, since electrons that transpose this region reaching the BC are available for electrical conduction.

The techniques for fabrication of semiconductors heterostructures made up of alternating layers of two semiconductor materials, have experienced great progress, thanks mainly to the development of the epitaxial crystal growth machines by molecular beam the known MBE machines. In these semiconductor heterostructures, it is possible to confine electronic systems with dimensions smaller than three, which are capable of exhibit electronic properties never before observed. Thus we can work with two-dimensional, one-dimensional and even zero-dimensional electronic systems simply changing the shape of the confinement potential barrier. The fundamental characteristic that allows the fabrication of abrupt one-dimensional potentials at the interface between GaAs/AlGaAs is the perfect match of the lattices constants that are approximately equal. Thus, by doping the barrier material (AlGaAs) with donor impurities, the electrons will migrate to the GaAs (the smaller gap material) and therein will be confined near the interface, forming a practically two-dimensional electron gas. A rectangular quantum wire is formed when an AlGaAs/GaAs/AlGaAs quantum well structure is bounded by two layers of AlGaAs grown along the y direction, as shown in the **Figure 1**. In this quantum well wire structure (QWW) a quasi-one-dimensional electron gas (Q1DEG) is confined in the GaAs semiconductor.

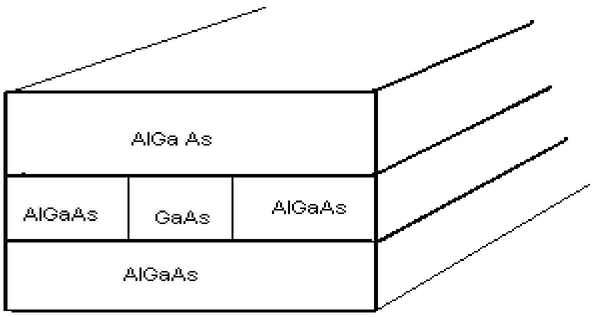

Figure 1. GaAs rectangular quantum well wire structure (QWW)

The Q1DEG confined in a semiconductor quantum well wire has motivated a great number of experimental and theoretical studies (Goñi et al. 1991; Auslaender et al. 2004; Farfad et al. 1995; Osório, Degani, and Hipólito 1989; Wang, Millis, and Sarma 2004; Paulo César Miranda Machado et al. 1997; Calmels and Gold 1998; Tavares 2005; Antonio Newton Borges, Leão, and Hipólito 1997; Hu and Das Sarma 1992; Demel et al. 1991; Wendler, Haupt, and Pechstedt 1991; Hwang and Das Sarma 1995; A.N. Borges, Osório,

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and Machado 2003; P.C.M. Machado, Osório, and Borges 2008; Cunha et al. 2004; Paulo César Miranda Machado, Borges, and Osório 2011) due to the potential application of the QWW in the electronic devices fabrication. The Q1D polaron gas present in these structures composed of polar semiconductors results from the coupling between the plasmons with the longitudinal optical (LO) phonon field and has been investigated theoretically by several authors in the last few years (Wendler, Haupt, and Pechstedt 1991; Hwang and Das Sarma 1995; A.N. Borges, Osório, and Machado 2003; P.C.M. Machado, Osório, and Borges 2008). The effects of the plasmon-LO phonon interaction (polaronic effects) cause a resonant split of the collective excitation energies of Q1D plasmons in GaAs-AlGaAs QWW in two branches: One branch with energy above and other branch with energy below the LO phonon energy. In the region of higher energies the plasmon-phonon interaction increases the energy of the plasma excitation and on the region of lower energies the polaronic effect reduces the plasma energy (Wendler, Haupt, and Pechstedt 1991; Hwang and Das Sarma 1995; A.N. Borges, Osório, and Machado 2003). More recently many body theoretical calculation have reported the observation of dips in the intrasubband static structure factor dispersion relation curves (Paulo César Miranda Machado, Borges, and Osório 2011), for Q1D plasmon confined in a GaAs-AlGaAs rectangular QWW. The authors shown that such dips are directly related with the resonant split of the lowest intrasubband plasmon-LO phonon collective excitation energy.

In this work we investigate the plasmon – LO phonon interaction effects on the intrasubband static structure factor and the plasmon energy associated with the lowest subband in GaAs-AlGaAs parabolic QWW as a function of the electronic density. Our calculations are performed using the Random Phase Approximation (RPA) at zero temperature. As is well known in the limit of low electronic densities (Cunha et al. 2004), the RPA approach is not recommended, therefore in this work we use values of the electronic density greater and smaller than the critical density to observe the effects on the structure factor and the collective excitations energies.

Theory

We consider a quantum wire consisting of GaAs that have a quasi-free electron gas movement along of the x-direction and with a confining potential in the plane (y,z) that quantize the electron movement in subbands. We assume the potential in the z-direction to have infinite height and in the y-direction a confining potential with parabolic form and subband separation energy □Ω (Antonio Newton Borges, Leão, and Hipólito 1997).

The screening potential, which takes into account the electron-electron interaction and the electron LO phonon interaction can be written as,

$$V_o(q_x,\omega) = \frac{2e^2}{\varepsilon_\infty}\int_0^\infty dk\,\frac{F(k,q_x)A(\omega)}{\sqrt{k^2+q_x^2}}, \tag{1}$$

with,

$$A(\omega) = \left[1 + \frac{2\omega_{LO}}{\hbar(\omega^2-\omega_{LO}^2)}\frac{\varepsilon_\infty\alpha(\hbar\omega_{LO})^2 r_p}{e^2}\right]. \tag{2}$$

In the precedent equations, ε_∞ is the high-frequency dielectric constant, ω_{LO} is the LO phonon frequency, α is the Frölich electron-phonon coupling constant and r_p is the polaron radius. The form factor which takes into account the QWW geometric form is given by,

$$F(k,q_x) = \int dy \int dy'\, |\varphi(y)|^2\, exp\left(-\sqrt{k^2+{q_x}^2}|y-y'|\right) \rightleftarrows |\rightleftarrows \varphi(y')|^2, \tag{3}$$

where the lowest subband wave function for the parabolic potential is given by,

$$\varphi(y) = \left[\frac{m\Omega}{\hbar\pi}\right]^{1/4} exp\left(-\frac{y^2}{2}\sqrt{\frac{m\Omega}{\hbar}}\right), \tag{4}$$

$S(q_x,\omega)$ is the static structure factor, defined as,

$$S(q_x) = -\frac{\hbar}{\pi\rho}\int_o^\infty d\omega\, Im[\chi(q_x,\omega)], \tag{5}$$

where ρ is the one dimensional electronic density. In the mean-field approximation the density-density response function of the system can be written as,

$$\chi(q_x,\omega) = \frac{P(q_x,\omega)}{1-V_o(q_x,\omega)P(q_x,\omega)}. \tag{6}$$

Where $P(q_x, \omega)$ is the RPA polarization function of the Q1D electron gas (Paulo César Miranda Machado, Borges, and Osório 2011).

RESULTS AND DISCUSSIONS

In the numerical calculation was considered a *GaAs – $Al_{0.3}Ga_{0.7}As$* parabolic QWW with two different values of the one dimensional electronic density, ρ = 2.91×10^5 cm^{-1} and ρ = 5.81×10^5 cm^{-1}. The values of the GaAs physical parameters used in the calculation were: effective Rydberg R_y=7,67*meV*, effective Bohr radius *a*=86*Å* and polaron radius r_p=*40Å*. The values assumed for the dielectric constants and for the optical phonon energies are respectively given by: ε_o=12 (static), ε_∞=10.9 (high frequency), $\hbar\omega_{LO} = 36.18meV$ and $\hbar\omega_{TO} = 33.29meV$.

Fig.2(a) shows the theoretical results for the lowest intrasubband collective excitation energy (left axis) as a function of the dimensionless one-dimensional electron wave vector with (dotted lines) and without (solid line) the plasmon-phonon interaction for parabolic QWW with $\hbar\omega$=2.5*meV* and ρ = 5.8×105 cm^{-1}. The shaded region denotes the single particle region. As one can observe from Fig.2(a) the inclusion in the calculation of the polaronic effects (dotted lines) cause a resonant split of the collective excitation energy in two branches, one with energy below and other with energy above the LO-optical phonon energy $\hbar\omega_{LO}$=4.72Ry* (straight horizontal). Note that in the lower branch of the energy the polaronic effect decreases the values of the collective excitation energy as expected. In the region around q_x=1 both curves plunge in the single particle region where the collective modes are damped. The results for the static structure factor dispersion are also included in Fig.2(a) (right axis). As one can see the structure factor curve dip is directly related to the resonant split of the collective excitation energy. The oscillation of the structure factor dispersion relation curve is a signature of the oscillator strength transfer from the lower branch to the higher branch of the collective excitation energy.

Fig. 2 (b) shows a similar result to that shown in Fig. 2 (a), but for ρ = 2.9×10^5 cm^{-1}, value smaller than the critical electronic density, that in this case is ρ = 3.5×10^5 cm^{-1}. The main difference between these results lies in the structure factor relation dispersion curve,

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that present oscillations and an inverted peak more abrupt and depth that it was observed in Fig.2(a). Also in Fig. 2 (b) can be noted a second inverted peak inside the region of the single particle, which does not appear in Fig.2 (a). This second peak in the structure factor spectra can be related with the limitations of the RPA approach. As well-known, this calculation method does not provide acceptable physical results for the pair correlation function for low electronic densities, i.e., for small interparticle separation and low electronic densities the RPA gives negative values for the pair correlation function. Therefore as this inverted peak in the single particle region disappears for higher electronic densities, we associated this result with the unsuitable calculation method. Also it is worth noting that the single particle region in Fig.2 (a) is larger than in Fig.2 (b). Particularly the oscillations in the structure factor relation dispersion curve, which are related with the transition of the oscillator strength of the lower branch to the higher branch of the collective excitation energy appears even when the local field correction (LFC) are incorporated in the calculations, as can be seen in reference (Paulo César Miranda Machado, Borges, and Osório 2011) for rectangular QWW.

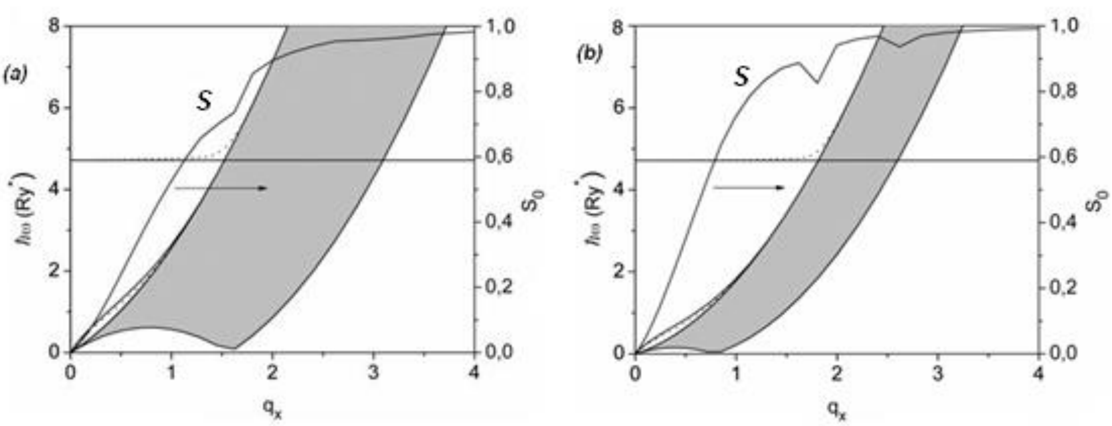

Fig. 2: Intrasubband static structure factor (right axes) and collective excitation energy (left axes) with (dotted lines) and without (solid lines) the polaronic effect for $\hbar\omega$=2.5meV and (a) ρ = 5.8×105 cm-1; (b) ρ = 2.9×105 cm-1.

CONCLUSION

In summary we have highlighted the crucial role of the semiconductor materials and devices in the development of today's technology. This technology helps in several ways the monitoring of human activities and estimates its consequences to the environment, these information can guide policies and actions to avoid the impacts of global warming. We also discuss the properties of semiconductors and in particular we consider a quasi-one-dimensional electron gas confined in a quantum wire. We have investigated the effects of the plasmon–(LO) phonon interaction on the intrasubband static structure factor and the plasmon energy associated with the lowest subband in GaAs-AlGaAs parabolic QWW as a function of the electronic densities. We observe the presence of oscillations in the static structure factor spectra and show that they are directly related to the resonant split of the intrasubband collective excitation energy.

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