Carrier-Acoustic Plasmon Instability in Semiconductor Quantum Wires

M. Bonitz,[(a)] R. Binder, and S. W. Koch

Optical Sciences Center and Physics Department, University of Arizona, Tucson, Arizona 85721

(Received 28 December 1992)

A novel carrier-acoustic instability is predicted for quasi-one-dimensional plasmas in semiconductor quantum wires with nonequilibrium carrier distributions. The complete collective excitation spectrum of the one-dimensional quantum plasma is obtained solving the complex dispersion relation in the random-phase approximation.

PACS numbers: 73.20.Dx, 52.35.Fp, 52.35.Qz, 71.45.Gm

Since the experimental realization of quasi-one-dimensional (1D) semiconductor quantum wires [1] the understanding of collective plasma waves in 1D systems has become an issue of considerable current interest [2–10]. 1D plasmons are well established experimentally and even the dispersion of the modes could be measured recently [11]. Random-phase-approximation (RPA) calculations of the intraband and interband excitation spectra in equilibrium ($T=0$) have been carried out including details of the electronic structure, such as coupling between bands, impurities, carrier-carrier scattering, and doping [9,10]. However, the dispersion relations have been obtained only in the limit of vanishing damping, yielding just that part of the collective excitation spectrum which consists of the undamped (usually the optical) modes.

In this Letter we show that a proper analytic continuation of the dielectric function into the lower energy half plane [12] reveals additional collective modes, which are Landau damped. As a surprising result, we find for 1D plasmas in low temperature equilibrium a second intraband excitation for each plasma component. This agrees well with recent experiments, where two such intraband excitation peaks have been observed [11].

Optically generated plasmas in quantum wires are composed of electrons and holes, requiring the study of plasmons in a two-component system. For such a system we find that the particular properties of the 1D pair continuum allow the undamping of collective excitations of the heavy particles, even in equilibrium.

The study of 1D plasmons is by no means restricted to quantum wires, but is also of interest to other physical systems like ionized gases, metallic wires [13], organic conductors, and metallic polymers. However, in contrast to the model of a single quasi-1D metal, organics and polymers have to be thought of as arrays of 1D filaments [14] or, in the corresponding continuum limit, as strongly anisotropic 3D systems [15]. As a consequence of the interfilament Coulomb interaction, the physical properties, and in particular the zero wavelength limit of the optical plasmon frequency exhibit a quasi-3D character (i.e., a nonzero value) [16].

1D plasma instabilities have been analyzed also for ionized gases, where nonequilibrium electron and ion distributions are generated through application of external fields or through highly energetic particle beams. Furthermore, the system's response for nonequilibrium situations has been studied in metallic wires in recent heating experiments [13]. Investigations of this kind lead to the interesting question of plasma instabilities in quantum wires as well as in 1D organics and polymers. The main purpose of this Letter is to predict a novel carrier-acoustic instability in such systems and to identify conditions for its occurrence.

Plasmon dispersions are computed from the zeros of the complex dielectric function, which within the RPA is [17]

$$\epsilon(\omega_r,\gamma,q)=1-V(q)\sum_a \Pi_a(\omega_r,\gamma,q),\quad a=e,h\,. \tag{1}$$

Here, ω is the complex frequency $\omega=\omega_r+i\omega_i=\omega_r-i\gamma$, where γ is not restricted to infinitesimal small values. The 1D intraband polarization function Π_a in (1) is

$$\Pi_a(\omega_r,\gamma,q)=(2s_a+1)\int_C \frac{du}{2\pi}\frac{f_a(u+q)-f_a(u)}{E_a(u+q)-E_a(u)-(\omega_r-i\gamma)}\,, \tag{2}$$

where s_a is the spin, $E_a(k)=k^2/2m_a$, and $\hbar=1$. In Eq. (1) $V(q)$ is the Coulomb potential and f_a the 1D carrier distribution function normalized to the average 1D density. In our numerical calculations we used $V(q)=2e^2\times K_0(qd)/\epsilon_b$ for a one-band quantum wire. Here K_0 denotes the modified Bessel function of the second kind, d is the wire width, and ϵ_b is the background dielectric constant [5]. This potential corresponds to the real space potential $V(x)\sim(x^2+d^2)^{-1/2}$ [17]. In the case of 1D systems without quantum confinement, like ionized gases, metal wires, or organics we would have to use $V(q)\sim 1/q^2$, but our analysis reveals that this difference in Coulomb potentials leads only to minor modifications of the results.

Figure 1(a) shows the result of the analytic continuation of the polarization (2) into the lower half plane of complex energy (frequency) for an electron-hole plasma at $T=0$. The two pair continua are bounded by the lines $\omega_{1a}(q)=qk_F/m_a+E_a(q)$ and $\omega_{2a}(q)=qk_F/m_a-E_a(q)$,

0031-9007/93/70(24)/3788(4)$06.00

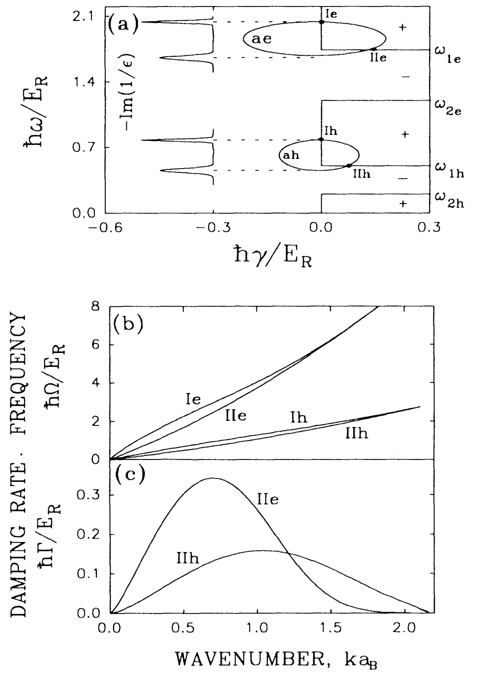

FIG. 1. Collective intraband excitations and pair continua in an electron-hole plasma at $T=0$. (a) Analysis of the dielectric function (analytic continuation) in the complex energy plane and spectral function $-\mathrm{Im}(1/\epsilon)$ for a fixed wave number (qualitative picture, arbitrary units). Curves *ae* and *ah* are the location of the zeros of $\mathrm{Re}(\epsilon)$, essentially corresponding to the electrons and the holes, respectively. The rectangular lines correspond to $\mathrm{Im}(\epsilon)=\mathrm{Im}(\Pi)=0$, separating the areas of positive and negative signs of $\mathrm{Im}(\Pi)$ (indicated by "+" and "−," respectively). Collective excitations are associated with zeros of the dielectric function, i.e., with the points I*e*, II*e* (optical and acoustic plasmon of the electrons), and I*h*, II*h* (undamped and damped plasmons of the holes). The pair continua of the electrons and the holes correspond to the gaps between ω_{1e},ω_{2e} and ω_{1h},ω_{2h}, respectively. (b) Plasmon frequencies (I, optical and II, acoustic plasmons) vs wave vector. (c) Landau damping coefficients of the acoustic plasmons. The modes I*e* and I*h* are undamped. The parameters are chosen for GaAs (Rydberg units, $\hbar=1$): $\epsilon_b=12.7$, $E_R=4.2$ meV, $m_e/m_{\mathrm{red}}=1.284$, $m_h/m_{\mathrm{red}}=4.522$, $a_B=135$ Å, $d=100$ Å, $k_F=1.9/a_B$, $n=1.2/a_B$.

$a=e,h$. Collective excitations correspond to the complex zeros, $\Omega(q)-i\Gamma(q)$, of the dielectric function, i.e., to the crossing points of the lines $\mathrm{Re}(\epsilon)=0$ (*ae*,*ah*) and $\mathrm{Im}(\epsilon)=0$ (rectangular lines). In addition to the optical plasmon of the electrons (point I*e*), we find an undamped plasmon of the holes (I*h*). This result is a peculiarity of 1D systems where a nonzero lower boundary of the pair continuum $\omega_{2i}(q)$ exists. (In 2D and 3D equilibrium plasmas the low momentum part of the pair continuum of the heavy species is always embedded in the pair continuum of the lighter particles.) In a two-component 1D plasma the overlap of both pair continua opens a "window" [between lines $\omega_{1h}(q)$ and $\omega_{2e}(q)$ in Fig. 1(a)] for the oscillations of the heavier species. The existence of a gap in the 1D intersubband pair continua, leading to plasmons not being Landau damped, has already been pointed out in [11]. This result is quite general and can be extended to plasmas consisting of more than two components or to other 1D systems. Especially for fully ionized gases with degenerate ions the possibility of undamped oscillations of the ions, even in equilibrium, is an important new result.

In addition to the two undamped plasmons there are two more zeros of the dielectric function in Fig. 1(a): points II*e* and II*h*, lying at the upper edge of the continua. Since these modes are obtained as solutions of the complex dispersion relation they have to be interpreted as collective excitations, i.e., as damped acoustic plasmons of the electrons and holes, respectively. These modes cause well pronounced peaks of the spectral function $-\mathrm{Im}[\epsilon^{-1}(\omega_r,\gamma=0,q)]$ that lie inside the pair continuum [18]. The two plasmons of the electrons, which occur already in a one-component system, closely resemble the peaks measured by Goñi *et al.* [11]. The wave vector dispersion and the Landau damping rates of the modes are given in Figs. 1(b) and 1(c).

To analyze nonequilibrium two-component plasmas in 1D we study the solution of Eq. (1) graphically, as shown in Fig. 2(a) for the case of an electron plasma. Necessary for the occurrence of an instability is a minimum of the distribution function which can be realized, e.g., by adding carriers in high momentum states to a thermal plasma. This minimum causes a "damping inversion," i.e., positive values of $\mathrm{Im}(\Pi)$ at $\gamma=0$, and, hence, zeros of $\mathrm{Im}(\epsilon)$ at negative γ [line *b* in Fig. 2(a)]. However, this is not a sufficient condition for a plasmon instability. An unstable mode arises only if the energy provided by the nonequilibrium carriers is high enough and can be transferred to growing oscillations of the thermal carriers. In Fig. 2(a) this corresponds to a crossing of line *b* with the lines $\mathrm{Re}(\epsilon)=0$ in the $\gamma<0$ half plane (elliptic lines *a'* or *a*, respectively). Such a crossing happens only if there is an overlap of the lines corresponding to the thermal carriers (the line *a'* at low frequency) and the nonthermal carriers [point IV in Fig. 2(a)]. The highest efficiency of the interaction between thermal and nonequilibrium carriers is observed if the average momentum of the nonequilibrium carriers approaches the Fermi edge and if the Coulomb interaction is strong. Quantum wires provide the unique feature to allow control of this interaction by changing the width of the wire. An even stronger instability should occur in 1D plasmas without quantum confinement, i.e., different form of the Coulomb potential.

In order to obtain a qualitative picture of the instability we consider the limiting case $f_{\mathrm{NEQ}}(k)=\Theta(k_F-k)\times\Theta(k)+\Theta(k_4-k)\Theta(k-k_3), k\geq 0$, $f(-k)=f(k)$, $k_F<k_3<k_4$ [19,20]. The results are shown in Figs. 2(b) and 2(c). The generalization to many-component plasmas yields the possibility of one unstable mode for each

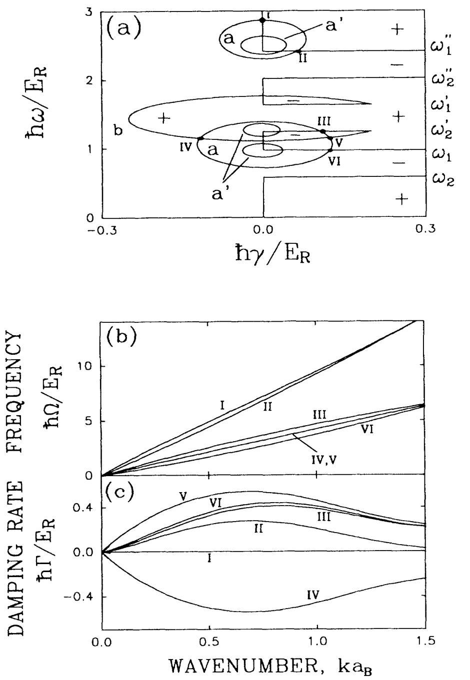

FIG. 2. Plasmon dispersion for a nonequilibrium electron plasma with the distribution function $f_{\rm NEQ}$. The parameters are $k_F=1.9/a_B$, $k_3=1.84k_F$, $k_4=k_3+k_F$. (a) Analysis of the dielectric function (analytic continuation) in the complex energy plane for a constant wave vector (qualitative picture). The pair continua correspond to the gaps between ω_1'',ω_2'' and ω_1,ω_2, respectively, with $\omega_{1,2}=qk_F/m\pm E(q)$ and $\omega_{1,2}''=qk_4/m \pm E(q)$. The signs of Im($\Pi$) are indicated by "+" and "−," respectively. The inversion region [between ω_1',ω_2', with $\omega_{1,2}'=qk_3/m\pm E(q)$] causes a deformation of the rectangular lines Im(ϵ) =0 into the left half plane (line b). Re(ϵ) =0 along the ellipses which are shown for a thin wire (a: $d\sim 100$ Å) and a thicker one (a': $d\sim 200$ Å). Plasmons are labeled I–VI for the case of the thin wire. The unstable mode IV occurs only for the thin wire. (b) Dispersion of the six plasmon modes (thin wire). The unstable (stable) pair IV (V) has the same frequency. (c) Landau damping rates of the plasmons (thin wire). The unstable mode IV has a negative "damping" rate; the optical plasmon I is undamped.

component. Analyzing the nature of the instability, we find that the frequency can be well approximated by $\Omega_{\rm inst}(q)\approx(\Omega_{\rm III}+\Omega_{\rm VI})/2=(k_F+k_3)q/m$ yielding a constant phase and group velocity $v_{\rm inst}=(k_F+k_3)/m=$const. These conditions describe a *carrier-acoustic instability* causing a plasma wave which initially propagates without dispersion. Driven by the fast nonequilibrium charge carriers the amplitude of the wave is growing until it becomes damped and possibly stabilized by other nonlinear mechanisms beyond the RPA, like, e.g., carrier-carrier or carrier-phonon scattering. Such an instability should be observable, e.g., for optically generated nonequilibrium carrier distributions in quantum wires.

At this point it is interesting to investigate to which degree our results are a special feature of the RPA dielectric function at $T=0$. Benner and Haug [7] have shown that the RPA does not lead to intrinsic contradictions if the electron density exceeds the inverse bulk exciton Bohr radius by a factor of 1.5. Our parameters are close to this value. Checking the influence of finite temperature we find with growing temperature a continuous deformation of the lines Re(ϵ) =0 and Im(ϵ) =0. All plasmons survive, only their damping increases [21].

We furthermore considered the influence of carrier-carrier and carrier-phonon scattering. Recent time resolved luminescence measurements [22] as well as Monte Carlo simulations [23] suggest that the scattering rates are reduced compared to the bulk case, yielding relaxation times τ_R exceeding 1 ps. Based on these results we used a relaxation time approximation according to Mermin [24] in order to account for collisions in the dielectric function. For τ_R up to 0.5 ps the result was mainly a shift of the lines Re(ϵ) =0 and Im(ϵ) =0 toward higher damping. The damping coefficients of all plasmons were increased approximately by $1/\tau_R$.

In conclusion, we have investigated the collective excitation spectrum of quasi-one-dimensional one-band quantum plasmas on the basis of the analytic continuation of the RPA polarization. Our new result for many-component plasmas in equilibrium ($T=0$) is the prediction of one undamped oscillation for each one of the heavy species (one mode per different mass), which is in contrast to 2D and 3D systems. Furthermore, we find that in addition to the undamped plasmon, each plasma component has a second, damped plasmon mode. The origin of this mode is the particular properties of 1D systems, which lead to a sharp peak of the spectral function close to the upper edge of the pair continuum (at $\gamma=0$). For nonequilibrium carrier distributions we predict growing acoustic plasmon modes in quantum wires. The strongest effect is expected for thin wires. Frequency and growth rates of the unstable plasma excitations depend strongly on the shape of the distribution function and, hence, can be influenced experimentally.

This work is supported by grants from the NSF, ARO/AFOSR(JSOP)NEDO,OCC and a grant for CPU time at the Pittsburgh Supercomputer Center. M.B. acknowledges discussions with D. Kremp and K. Morawetz (Rostock) and financial support by the Deutscher Akademischer Austauschdienst (DAAD).

[a]Permanent address: Universität Rostock, Fachbereich Physik, Universitätsplatz 3, O-2500 Rostock, Germany.

[1] J. Cibert, P. M. Petroff, G. J. Dolan, S. J. Pearton, A. C. Gossard, and H. J. English, Appl. Phys. Lett. **49**, 1275 (1986).

[2] T. Egeler, G. Abstreiter, G. Weimann, T. Demel, D. Heitmann, P. Grambow, and W. Schlapp, Phys. Rev. Lett. **65**, 1804 (1990).

[3] T. Demel, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. Lett. **66**, 2657 (1991).
[4] I. Grodnensky, D. Heitmann, and K. von Klitzing, Phys. Rev. Lett. **67**, 1019 (1991).
[5] S. Das Sarma and Wu-yan Lai, Phys. Rev. B **32**, 1401 (1985).
[6] Jin Wang and J. P. Leburton, Phys. Rev. B **41**, 7846 (1990).
[7] S. Benner and H. Haug, Z. Phys. B **84**, 81 (1991).
[8] Ben Yu-Kuang and S. Das Sarma, Phys. Rev. Lett. **68**, 1750 (1992).
[9] Q. P. Li and S. Das Sarma, Phys. Rev. B **43**, 11768 (1991).
[10] A. Gold and A. Ghazali, Phys. Rev. B **41**, 7626 (1990).
[11] A. R. Goñi, A. Pinczuk, J. S. Weiner, J. M. Calleja, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **67**, 3298 (1991). They present the results of resonant inelastic polarized light-scattering experiments on quantum wires. Their Fig. 1 shows two intraband excitation peaks, explained as optical plasmon and "predominantly single-particle excitation," respectively.
[12] See, e.g., W.-D. Kraeft, D. Kremp, W. Ebeling, and G. Röpke, *Quantum Statistics of Charged Particle Systems* (Akademie-Verlag, Berlin, 1986).
[13] J. Seyler and M. N. Wybourne, Phys. Rev. Lett. **69**, 1427 (1992).
[14] I. E. Dzyaloshinksii and E. I. Kats, Zh. Eksp. Teor. Fiz. **55**, 338 (1969) [Sov. Phys. JETP **28**, 178 (1969)].
[15] J. Ruvalds, F. Bosens, L. F. Lemmens, and J. T. Devreese, Solid State Commun. **23**, 243 (1977).
[16] P. F. Williams and Aaron N. Bloch, Phys. Rev. B **10**, 1097 (1974).
[17] H. Haug and S. W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors* (World Scientific, Singapore, 1993), 2nd ed.
[18] Notice that the second zero of Re(ϵ) (at $\gamma=0$) occurs in 2D and 3D systems too. But the procedure of the analytic continuation is here far more complicated. Therefore the question, if this zero can be associated with a collective excitation in this case too, we cannot answer definitely at the moment. But in contrast to 1D systems this mode would be strongly damped.
[19] D. C. Scott, R. Binder, and S. W. Koch, Phys. Rev. Lett. **69**, 347 (1992).
[20] K. El Sayed, R. Binder, D. C. Scott, and S. W. Koch, Phys. Rev. B **47**, 10210 (1993).
[21] Details of the calculations will be given in M. Bonitz, R. Binder, D. C. Scott, S. W. Koch, K. Morawetz, and D. Kremp (to be published).
[22] R. Cingolani, H. Lage, H. Kalt, D. Heitmann, and K. Ploog, Phys. Rev. Lett. **67**, 891 (1991).
[23] L. Rota, F. Rossi, S. M. Goodnick, P. Lugli, E. Molinari, and W. Porod, Phys. Rev. B **47**, 1632 (1993).
[24] N. D. Mermin, Phys. Rev. B **1**, 2362 (1970).