Coherence of Elementary Excitations in a Disordered Electron System

Yu. A. Pusep,[1] M. B. Ribeiro,[1] V. E. Carrasco,[2] G. Zanelatto,[2] and J. C. Galzerani[2]

[1]*Instituto de Fisica de São Carlos, Universidade de São Paulo, 13560-970 São Carlos, São Paulo, Brazil*

[2]*Departamento de Fisica, Universidade Federal de São Carlos, CP 676, 13565-905, São Carlos, São Paulo, Brazil*

(Received 7 January 2004; revised manuscript received 22 December 2004; published 8 April 2005)

The localization properties of the single-particle and collective electron excitations were investigated in the intentionally disordered GaAs/AlGaAs superlattices by weak-field magnetoresistance and Raman scattering. The localization length of the individual electron was found to be considerably larger than that of the collective excitations. This suggests that the disorder has a weaker effect on the electrons than on their collective motion and that the interaction which gives rise to the collective effects increases localization.

DOI: 10.1103/PhysRevLett.94.136407 PACS numbers: 71.45.-d, 71.23.An, 71.55.Jv, 72.15.Rn

According to Kohn [1], electron localization occurs in configuration space and, therefore, relates to the wave nature of an electron rather than to the distribution of the electron charge density in real space. Consequently, the insulating state, which results in a zero dc conductivity, is determined by the localization of the ground wave function. Therefore, a direct probe of the properties of the wave function is a central subject of the localization problem. Any elementary excitations having a wave origin reveal the same qualitative aspects of localization. However, their specific features may result in different characteristic performances. A generality of the localization in the cases of the individual electrons and their collective motions (plasmons) was first pointed out in Ref. [2], where the random semiconductor superlattices (SLs) were also proposed as a tool to control the strength of the disorder. The essential difference between electrons and plasmons is in the dynamic polarization which determines the collective electron motion. Hence, the interaction between electrons intrinsically determines features of their collective excitations (plasmons). Therefore, the comparison between the localization properties of the plasmons and the electrons may shed some light on the problem of how the interaction influences localization. It is pertinent to mention that Dirac pointed out that "if we wish to make an observation on a system of interacting particles, the only effective method of procedure is to subject them to a field of electromagnetic radiation and see how they react" [3].

In this way the phase-breaking length of the individual electrons can be obtained by the weak-field magnetoresistance measurements [4]. As it was stated in Ref. [5], the phase-breaking length determines the minimum width of an electron wave packet and, therefore, it may serve as the lower cutoff for the localization length. On the other hand, the localization length associated with the indetermination of the quasimomentum of plasmons can be measured by Raman scattering [6].

In strongly disordered bulk materials the Landau damping determines the localization length of plasmons [7], whereas the quantization of the electron energy in superlattices sets new limits. Namely, the disorder determines the localization of plasmons when their energy is placed in the range of the minigap of the single-particle spectrum. Therefore, a direct comparison between the disorder induced localization properties of the single particle and the collective electron excitations is possible for those propagated along the quantization direction (perpendicular to the layers). In such a case the vertical magnetotransport may be measured only in low doped superlattices (to decrease as much as possible a contribution from the substrate), while Raman scattering allows one to measure the plasmon localization length in relatively high doped structures. Therefore, it is difficult to find samples where both these methods may be applied simultaneously. In this work we used the intentionally disordered GaAs/AlGaAs SLs where the vertical (along the growth direction) disorder was produced by a random variation of the well thicknesses. Such a disorder let us control the spatial extent of the wave functions of the elementary excitations propagating normal to the layers and choose the structure of the samples where the localization properties of both the electrons and the plasmons can be measured concurrently.

Two pairs of the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ SLs (where the thicknesses of the layers are expressed in monolayers) with different disorder strengths and doping concentrations were grown on (001) GaAs substrates. Each pair consisted of two identical SLs, one grown on a semi-insulating substrate and another grown on a doped one. They were used to measure the parallel and vertical magnetotransport, respectively. To form the degenerate electron system the samples were homogeneously doped with Si. The disorder strength was characterized by the disorder parameter $\delta_{SL} = \Delta/W$, where Δ is the width of a Gaussian distribution of the electron energy and W is the miniband width of the nominal SL (with $m = 17$ ML) in the absence of disorder. The samples with $\delta_{SL} = 0.4$ and $\delta_{SL} = 0.8$ and with the total thickness 0.3 μm (50 periods) and 0.9 μm (150 periods), respectively, were studied. A contact 0.4 μm thick highly doped GaAs layer was deposited on the top of the SLs grown on a doped substrate. This top layer was removed before the Raman measurements.

The samples were patterned into either Hall bars or square shaped mesa structures with areas $1 \times 1\ \mathrm{mm}^2$ [shown in insets of Fig. 1(c)]. The Ohmic contacts were fabricated by depositing either an In (Hall bars) or an Au:Ge:Ni alloy (mesas). All magnetotransport measurements were performed in the transversal geometry with the current 10^{-5}–10^{-4} A using the standard low-frequency (1 Hz) lock-in technique in the temperature range from 1.6 to 80 K. The vertical magnetoresistances were acquired by two-probe measurements in a double mesa structure consisting of two identical mesas connected in series. A direct comparison with the four-probe vertical measurements did not reveal significant contact resistances as in Ref. [8], where a comprehensive analysis of the unavoidable monolayer fluctuations on the vertical transport of GaAs/AlGaAs SLs was presented. The collective excitations propagated normal to the layers were examined with Raman scattering performed at $T = 10$ K with a "Instruments S.A. T64000" triple grating spectrometer; the 5145 Å line of an Ar^+ laser was used for nonresonant excitation. Raman scattering of the collective excitations propagated along the layers was collected from the (110) side of the SL with the total thickness $d_{\mathrm{SL}} = 0.9\ \mu$m. In order to avoid scattered light coming from the substrate, the micro-Raman system which focused the light with a spot size smaller than 1 μm was used. In this case the Raman spectra were taken at $T = 80$ K.

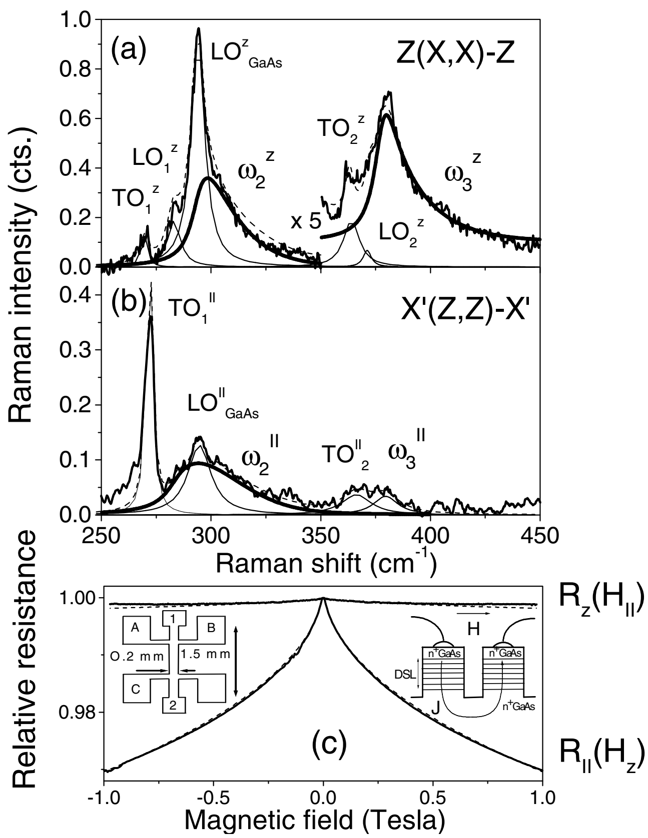

FIG. 1. Raman intensities of the collective modes propagated (a) perpendicular and (b) parallel to the layers measured at $T = 80$ K in the $(\mathrm{GaAs})_m(\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As})_6$ superlattice with the disorder strength $\delta_{\mathrm{SL}} = 0.8$. The calculated contributions of the asymmetrical plasmonlike peaks are shown by thick lines. (c) The parallel and vertical magnetoresistances measured in the same superlattice at $T = 1.6$ K. The dashed lines were calculated. Insets: the Hall bar and the double superlattice mesa used for the parallel and vertical transport measurements, respectively.

In recent articles [6] we have demonstrated that in the intentionally disordered GaAs/AlGaAs SLs the observed asymmetry of the Raman lines associated with the plasmonlike collective excitations is due to the effect of their localization. In this case the magnitude of the localization length of the relevant collective excitations indicates the strength of the correlation effects (the longer localization length, the stronger electron correlation), and it can be determined using the formula [6]

$$I(\omega) \sim \int \exp\left[-\frac{(q-q_0)^2 L_p^2}{4}\right] \frac{dq}{[\omega - \omega_p(q)]^2 + (\Gamma/2)^2}, \tag{1}$$

where $q_0 = 4\pi n(\lambda)/\lambda$ is the wave number transferred by the laser light with the wavelength λ used for excitation, $n(\lambda)$ is the refractive index, and $\omega_p(q)$, L_p, and Γ are the dispersion of the appropriate collective excitations, their localization length, and their damping constant, respectively. The dispersions of the collective modes were calculated in the direction of propagation of the light using the random phase approximation (RPA) as in Ref. [6]. In the absence of Landau damping, the validity of the RPA was confirmed in Ref. [7].

The high-field magnetoresistance data that display the distinct Shubnikov–de Haas oscillations (they were used to determine the Fermi energies given in Table I) and the absence of the activation-type temperature behaviors of resistances show the metallic properties of the electrons subjected to a weak anisotropic disorder.

In the weak localization regime ($k_F l \gg 1$) and in a weak magnetic field ($\omega_c\tau \ll 1$, where ω_c and τ are the cyclotron frequency and the elastic scattering time, respectively) the quantum correction to the transversal parallel magnetoconductivity of a SL is determined by the following expression [9]:

$$\Delta\sigma_{\parallel}(H) = \frac{e^2}{2\pi^2\hbar l_H}\alpha F(\delta), \tag{2}$$

TABLE I. Parameters determined at $T = 10$ K in two types of the studied disordered GaAs/AlGaAs superlattices.

δ_{SL}	n_H (cm^{-3})	μ_H ($\frac{\mathrm{cm}^2}{\mathrm{V\,s}}$)	E_F (eV)	$k_F l$	$L^z_{p^3}$ (nm)	L^z_{φ} (nm)
0.4	6.5×10^{17}	1400	0.036	5.9	5.0	250.0
0.8	2.0×10^{17}	2143	0.015	4.0	7.3	140.0

where $l_H = \sqrt{\hbar/eH_\perp}$ is the magnetic length, $\alpha = \sqrt{m_z/m_\parallel}$ is the coefficient of anisotropy (in the SLs studied here the calculations give $\alpha = 1.4$), $F(\delta)$ is the Kawabata function, and $\delta = \frac{l_H^2}{4L_\varphi^2}$ with L_φ being the electron phase-breaking length. The correction to the vertical transversal magnetoconductivity of a SL is given by the formula (2) divided by α^2 with the magnetic field determined by the scaling relation $H_\parallel = H_\perp/\alpha$ [10].

The Raman scattering intensities obtained at $T = 80$ K in the $z(x,x)\bar{z}$ and $x'(z,z)\bar{x}'$ backscattering configurations (where z is the growth [001] direction and $x \parallel [100]$, $x' \parallel [110]$) in the thick disordered SL are shown in Figs. 1(a) and 1(b). According to the selection rules, in both these cases the longitudinal optic (LO) vibrations are active [11]. In the $z(x,x)\bar{z}$ geometry we observed the intensive line at 294 cm^{-1} which consists of two components: one due to the unscreened LO GaAs-like phonon from the depletion surface layer and another is the ω_2^z coupled plasmon-LO phonon GaAs-like mode (the superscript means the direction of the mode propagation), which revealed the disorder induced asymmetry [6]. Also, the likely asymmetrical ω_3^z coupled AlAs-like mode was found around 380 cm^{-1}. The weak LO_1^z and LO_2^z lines were assigned to the GaAs-like and AlAs-like LO phonons of the $Al_{0.3}Ga_{0.7}As$ barriers, respectively, revealed due to the depletion layer. In such an alloy these modes are expected at 282 cm^{-1} and at 375 cm^{-1} correspondingly [12]. Moreover, we observed the disorder induced TO_1^z and TO_2^z phonon lines attributed to the GaAs well and to the $Al_{0.3}Ga_{0.7}As$ barriers respectively; their expected values are 272 and 363 cm^{-1} correspondingly. The Raman spectrum measured in the $x'(z,z)\bar{x}'$ geometry shows the same character as in Refs. [11,12]: the intensive forbidden TO phonons and the weaker LO phonons.

The fits of the Raman intensities calculated by Eq. (1) to the experimental spectra measured in different orientations allowed us to obtain the localization lengths of the plasmonlike excitations propagated in different directions. The results of the best fits are shown in Figs. 1(a) and 1(b). At $T = 80$ K we found $L_{p2}^z \simeq 3.5$ nm and $L_{p3}^z \simeq 2.1$ nm for the GaAs and AlAs plasmonlike excitations, respectively, propagated normal to the layers, and $L_{p2}^\parallel \simeq 8.4$ nm for the GaAs plasmonlike excitations propagated along the layers.

The energy spectra of the elementary excitations calculated in different directions from those investigated above SL are depicted in Fig. 2. For the parallel plasmonlike excitations the experimental wave number cutoff $(2\pi/L_{p2}^\parallel)$ was found to be in reasonable agreement with the limitation of their wave number due to the Landau damping. This demonstrates a precision and a reliability of the experimental method used to determine the localization length of the collective excitations. At the same time, the Landau damping does not influence the localization of collective excitations propagated perpendicular to the layers because of the significant difference between their energy and the energy of the lowest miniband of the single-particle excitations. Therefore, in this case the disorder induced localization length was extracted.

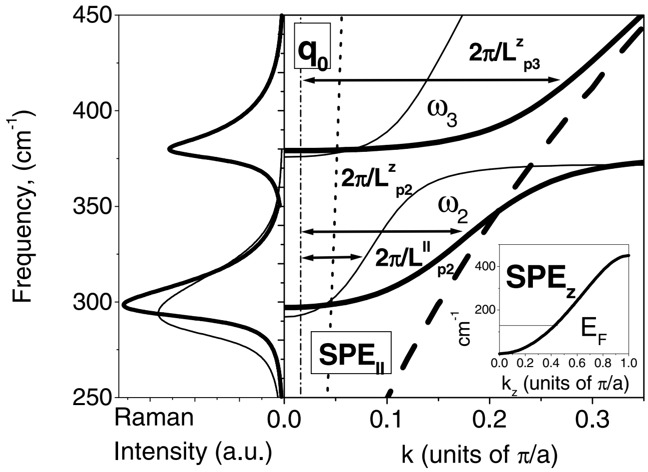

FIG. 2. Energy spectra of the vertically propagated single-particle (inset) and collective excitations calculated in the $(GaAs)_{17}(Al_{0.3}Ga_{0.6}As)_6$ superlattice with the electron concentration $n = 2.0 \times 10^{17}$ cm^{-3}. The dashed and full lines represent the dispersions of the uncoupled plasmons and the plasmons coupled to the LO phonons, respectively. Thin lines show the dispersions of the single-particle (dotted line) and collective excitations (full lines) propagated parallel to the layers. The vertical dash-dotted line demonstrates the wave number transferred by the light used for excitation. The left panel shows the corresponding calculated Raman intensities obtained by the fits as explained in the text.

In order to compare the disorder induced localization length of the collective excitations with that of the electrons, we measured Raman backscattering from the (001) surface of the SL at $T = 10$ K. The corresponding localization length of the GaAs plasmonlike excitations together with the vertical phase-breaking length obtained at the same temperature are given in Table I.

It should be mentioned that at low temperatures the electrons reveal strongly anisotropic negative magnetoresistance demonstrated in Fig. 1(c). The phase-breaking lengths obtained at $T = 1.6$ K in the directions perpendicular and parallel to the layers were 710 and 2200 nm, respectively. However, while the parallel phase-breaking length strongly decreased with the temperature, no significant temperature variation of the vertical phase-breaking length was observed. As a result, at $T = 10$ K the electrons already expose isotropic localization.

Similar results were obtained in another SL with a different disorder strength and a higher doping concentration. The Raman intensity measured in this SL is depicted in Fig. 3(a). We found the well pronounced plasmonlike asymmetry of the ω_3^z mode, while the ω_2^z mode exhibited the opposite phononlike asymmetry due to its phononlike character, as expected in highly doped SLs [6]. As in the previous case no effect of the Landau damping is antici-

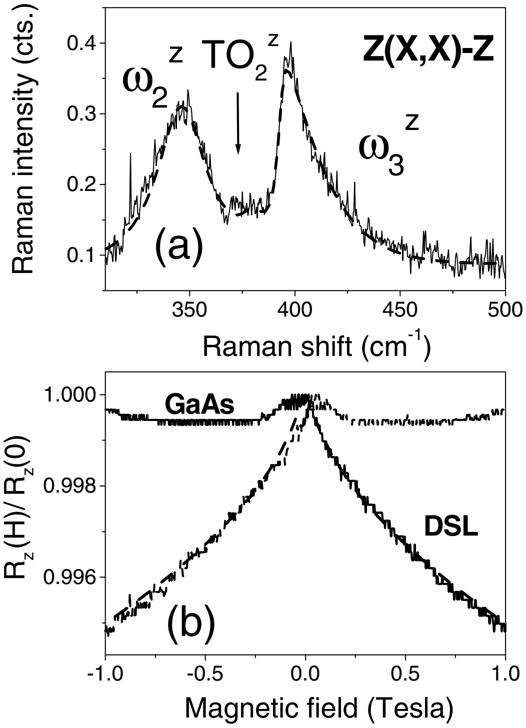

FIG. 3. (a) Raman intensity measured at $T = 10$ K in the $(GaAs)_m(Al_{0.3}Ga_{0.6}As)_6$ superlattice with the disorder strength $\delta_{SL} = 0.4$. (b) Weak-field vertical transversal magnetoresistance measured in the same superlattice at $T = 10$ K (labeled as DSL). The dashed lines were calculated. The data marked as GaAs relate to the mesa structure fabricated on the same doped substrate without the superlattice.

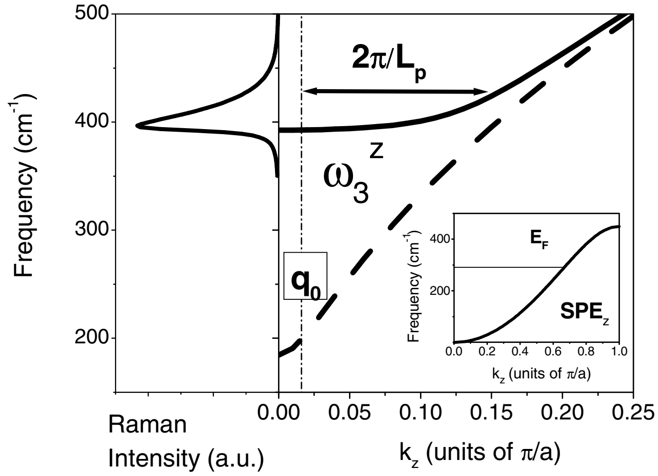

FIG. 4. Energy spectra of the vertically propagated single-particle (inset) and collective excitations calculated in the $(GaAs)_{17}(Al_{0.3}Ga_{0.6}As)_6$ superlattice with the electron concentration $n = 6.5 \times 10^{17}$ cm^{-3}. The dashed and full lines represent the dispersions of the uncoupled plasmons and the plasmons coupled to the AlAs LO phonons, respectively. The vertical dash-dotted line demonstrates the wave number transferred by the light used for excitation. The right panel shows the calculated Raman intensity obtained by the fit as explained in the text.

pated, and consequently disorder and the electron-electron interaction result in the localization length of the collective excitations shown in Fig. 4. The vertical magnetoresistance measured in the mesa structure prepared from this SL grown on a doped substrate is shown in Fig. 3(b) together with the data obtained in the mesa structure fabricated on the same doped substrate without the SL. The mesa-shaped GaAs substrate revealed no considerable magnetoresistance. Thus, the contribution from the substrate is negligible. The data obtained in this SL are given in Table I.

Finally, it is worth adding that the weak-field magnetoresistance in the disordered superlattices studied here is due to the quantum interference processes and is not caused by the interaction effects [13]. Therefore, a comparison between the localization lengths of the plasmonlike excitations and the phase-breaking lengths of the noninteracting electrons provides arguments for understanding the influence of the interaction on localization effects. The localization length of the collective excitations was found to be considerably smaller than that of the individual electron. This means that the disorder affects the collective excitations in a stronger way than it does the single-particle ones. Our data are in accord with the recent theoretical considerations of disordered correlated electron systems which demonstrate that the strong interaction decreases the localization length [14].

The financial support from FAPESP is gratefully acknowledged.

[1] W. Kohn, Phys. Rev. **133**, A171 (1964).
[2] S. Das Sarma, A. Kobayashi, and R. E. Prange, Phys. Rev. Lett. **56**, 1280 (1986).
[3] P. A. M. Dirac, Proc. R. Soc. London A **136**, 453 (1932).
[4] G. Bergmann, Phys. Rep. **107**, 1 (1984).
[5] B. L. Altshuler, A. G. Aronov, and D. E. Khmelnitsky, J. Phys. C **15**, 7367 (1982).
[6] Yu. A. Pusep, M. T. O. Silva, N. T. Moshegov, P. Basmaji, and J. C. Galzerani, Phys. Rev. B **61**, 4441 (2000).
[7] A. Pinczuk, G. Abstreiter, R. Trommer, and M. Cardona, Solid State Commun. **21**, 959 (1977).
[8] M. Lee, S. A. Solin, and D. R. Hines, Phys. Rev. B **48**, 11 921 (1993).
[9] W. Szott, C. Jedrzejek, and W. P. Kirk, Phys. Rev. B **40**, 1790 (1989).
[10] A. Cassam-Chenai and D. Mailly, Phys. Rev. B **52**, 1984 (1995).
[11] R. Hessmer, A. Huber, T. Egeler, M. Haines, G. Tränkle, G. Weimann, and G. Abstreiter, Phys. Rev. B **46**, 4071 (1992).
[12] S. W. da Silva, Yu. Pusep, J. C. Galzerani, M. A. Pimenta, D. I. Lubyshev, P. P. Gonzalez-Borrero, and P. Basmaji, Phys. Rev. B **53**, 1927 (1996).
[13] Yu. A. Pusep, H. Arakaki, and C. A. de Souza, Phys. Rev. B **68**, 205321 (2003).
[14] K. Byczuk, W. Hofstetter, and D. Vollhardt, Phys. Rev. Lett. **94**, 056404 (2005).