Coherence of Elementary Excitations in Disordered GaAs/AlGaAs Superlattices

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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 one of the collective excitations. This suggests that the disorder has weaker effect on the electrons than on their collective motion and that the interaction which gives rise to the collective effects increases localization.

Keywords: Coherence; Localization; Superlattices

The localization of elementary excitations rather relates to the wave nature of their wave functions than to the distribution of the electron charge density in the real space. Consequently, the insulating state, which results in a zero dc conductivity, is determined by the localization of the ground electron wave function. Therefore, a direct probe of the properties of the wave functions 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 firstly pointed out in Ref.[1], 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.

In this way the phase-breaking length of the individual electrons can be obtained by the weak-field magnetoresistance measurements [2]. As it was stated in Ref.[3], 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 quasi-momentum of plasmons can be measured by Raman scattering [4].

In strongly disordered bulk materials the Landau damping determines the localization length of plasmons [5]. 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 of them propagated along the quantization direction (perpendicular to the layers).

In this work we used the intentionally disordered $GaAs/AlGaAs$ SLs where the vertical (along the z growth direction) disorder was produced by a random variation of the well thicknesses. Such a disorder let us to control the spatial extent of the wave functions of the elementary excitations propagating normal to the layers and to choose the structure of the samples where the localization properties of both the electrons and the plasmons can be measured concurrently.

$(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ SLs (where the thicknesses of the layers are expressed in monolayers) with different disorder strengths and doping concentrations were grown on (001) $GaAs$ substrates. To form the degenerate electron system the samples were homogeneously doped with Si. The structures of the conduction band potential of the periodic and disordered SLs are shown in Fig.1. 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 $m = 17ML$) in the absence of disorder. The design of these SLs permitted to avoid the Landau damping of the collective high-frequency $AlAs$-like modes propagated normal to the layers. The Raman scattering of these modes was studied in the SLs with the electron densities $n = 1.7\text{x}10^{18}$ cm^{-3}.grown on semi-insulating substrates. While the vertical transport measurements were performed in the SLs with $n = 5.0\text{x}10^{17}$ cm^{-3} grown on doped substrates; these samples were patterned into square shaped mesa structures with areas 1x1 mm^2. The Ohmic contacts were fabricated by depositing an $Au : Ge : Ni$ alloy. All magnetotransport measurements were carried out in the transversal geometry with the current 10^{-5}-$10^{-4}A$ using standard low-frequency (1 Hz) lock-in technique at $1.6K$. The collective excitations propagated normal to the layers were examined with Raman scattering performed at $T = 10K$ with a "Instruments S.A. T64000 " triple grating spectrometer; the 5145 $\overset{o}{A}$ line of an Ar^+ laser was used for non-resonant excitation.

In the weak localization regime ($k_F l >>1$) and in a weak magnetic field ($\omega_c\tau <<1$, where ω_c and τ are the cyclotron frequency and the elastic scattering time respectively) the quantum correction to the vertical transversal magnetoconductivity of a SL is determined by the following expression [6]:

$$\Delta\sigma_{\shortparallel}(H) = \frac{e^2}{2\pi^2\hbar l_H \alpha} F(\delta) \tag{1}$$

where $l_H = \sqrt{\hbar/eH_\perp}$ is the magnetic length with the magnetic field determined by the scaling relation $H_{\shortparallel} = H_\perp/\alpha$, $\alpha = \sqrt{m_z/m_{\shortparallel}}$ is the coefficient of anisotropy (in the studied here SLs the calculations give $\alpha = 1.4$), $F(\delta)$ is the Kawabata function and $\delta = \frac{l_H^2}{4L_{\varphi z}^2}$ with $L_{\varphi z}$ being the electron phase-breaking length.

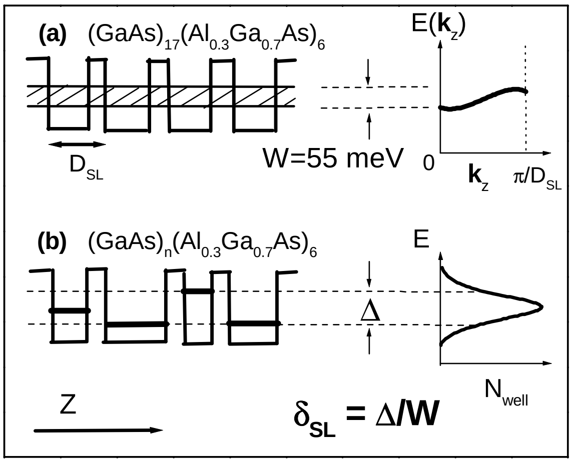

FIG. 1: Electron energy structures of the periodic (a) and disordered (b) *GaAs/AlGaAs* superlattices.

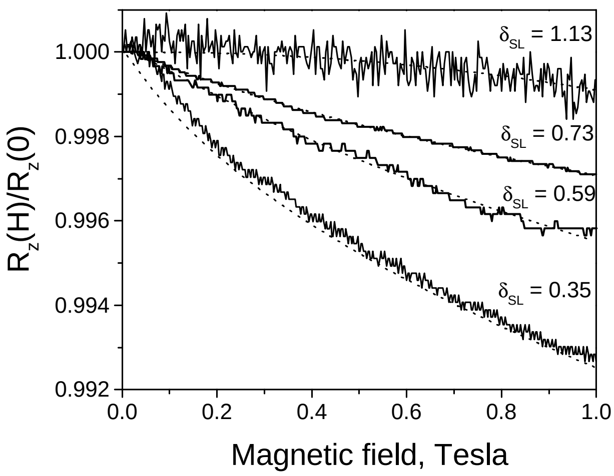

FIG. 2: Weak field relative vertical transversal magnetoresistance measured in the $(GaAs)_m(Al_{0.3}Ga_{0.6}As)_6$ superlattices with different disorder strengths at $T = 1.6\ K$. The dot lines were calculated according to Eq.(1).

The relative magnetoresistance traces measured in the SLs with different disorder strengths together with the corresponding calculated dependences are presented in Fig. 2. As it is seen, the disorder significantly reduced the negative magnetoresistance which is associated with the decrease of the electron phase-breaking length depicted in Fig. 4(a).

In the recent articles [4] we have demonstrated that in the intentionally disordered *GaAs/AlGaAs* SLs the observed

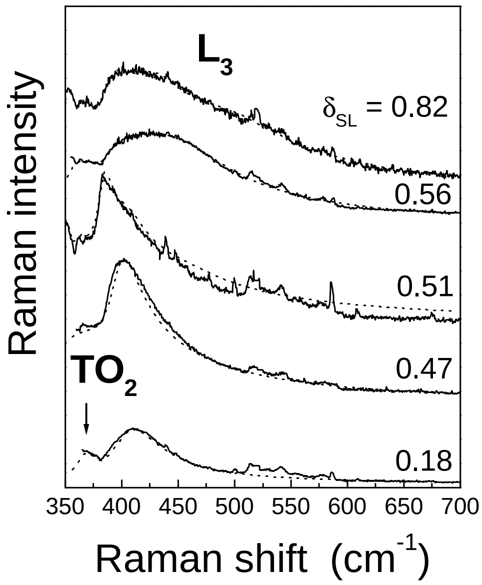

FIG. 3: Raman intensities measured in the $(GaAs)_m(Al_{0.3}Ga_{0.6}As)_6$ superlattices with different disorder strengths at $T = 10\ K$. The dot lines were calculated according to Eq.(2).

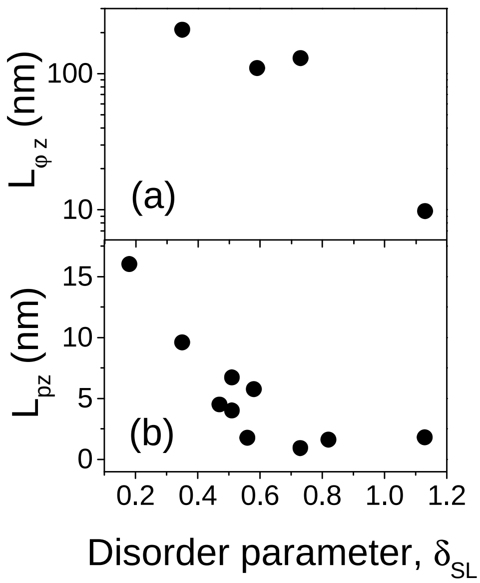

FIG. 4: Localization lengths of the single electrons (a) and their collective excitations (b) measured in the $(GaAs)_m(Al_{0.3}Ga_{0.6}As)_6$ superlattices with different disorder strengths and the fixed electron densities $n = 5.0x10^{17}cm^{-3}$ (a) and $n = 1.7x10^{17}cm^{-3}$ (b) respectively.

asymmetry of the Raman lines associated to the plasmon-like 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 [4]:

$$I(\omega) \sim \int \exp[-\frac{(q-q_0)^2 L_{pz}^2}{4}] \frac{dq}{[\omega-\omega_p(q)]^2+(\Gamma/2)^2} \quad (2)$$

where $q_0 = 4\pi n(\lambda)/\lambda$ is the wave number transferred by the laser light with the wave length λ used for excitation, $n(\lambda)$ is the refractive index, $\omega_p(q), L_{pz}$ 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.[4].

In order to compare the disorder induced localization lengths of the electrons with those of the collective excitations we measured Raman scattering from the (001) surface of the SL in the range of the *AlAs*-like lattice vibrations at $T = 10K$. The corresponding Raman intensities are shown in Fig.3. The collective *AlAs*-like coupled plasmon-*LO* phonon mode (L_3) revealed the typical asymmetry associated with the collective excitations. As it was mentioned above, this mode does not suffer the Landau damping; besides, it has mostly plasmon character. The fits of the Raman intensities calculated by Eq.(2) to the experimental spectra allowed us to obtain the localization lengths of the plasmon-like excitations propagated in the direction perpendicular to the layers. The results of the best fits are shown in Fig. 4(b).

Thus, the localization lengths of the single-particle and collective excitations, both propagated in the direction perpendicular to the layers, reveal considerable decrease with the increasing disorder strength. At this the localization lengths of the collective excitations were found significantly smaller than those of the electrons. This means that the disorder affects the collective excitations in a stronger way than it does to the single-particle ones.

Finally, it is worth adding that the weak-field magnetoresistance in the studied here disordered superlattices is due to the quantum interference processes and is not caused by the interaction effects [8]. Therefore, a comparison between the localization lengths of the plasmon-like excitations and the phase-breaking lengths of the noninteracting electrons provides arguments for understanding the influence of the interaction on localization effects.

Acknowledgments

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