Dipole excitations in a bilayer electron system in a parallel magnetic field

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The spectrum of neutral excitations of a bilayer electron system in an in-plane magnetic field is studied by means of inelastic light scattering spectroscopy. Tunnel induced interlayer excitation brunches are observed. They are basically of a single-particle nature with a linear dispersion law. In the asymmetrical state the interlayer excitations possess a large dipole moment normal to the layers. As a result, the excitation energies aquire an extra gauge term in magnetic field. In the symmetrical state the magnetic field redistributes electron wave functions in a way that a similar energy term arises. A method to determine the bilayer symmetry is suggested.

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Spatial confinement of electrons in a quantum well gives rise to intriguing effects which exist neither in two-dimensional nor in three-dimensional systems. Excitation branches related to electron transitions between different quantum subbands have attracted theoretical and experimental interest.[1–3] Excitation energies acquire an extra gauge term under an external magnetic field applied along quantum wells (QWs) (in-plane magnetic field) due to spatial separation of electron wave functions.[4] The wave functions are more widely separated in bilayer electron systems, so that the same effect is expected to be more pronounced for excitations involving electron transitions between the layers. Previously, an influence of in-plane magnetic field on the bilayer system was discussed in conductivity and cyclotron resonance experiments, where the parabolic dispersion curves from the two layers were shown to shift in the momentum space and to anticross. As a result, a minigap formed in the electron energy spectrum and two van Hove singularities developed in the density of states.[5,6]

Attention to bilayer electron systems has been renewed with a view toward studying quantum states with no analogies in single QWs. Easy plane and easy axis ferromagnetics, charge transfer instabilities, spontaneous symmetrization of the ground state, and exciton superconductivity have been predicted theoretically and have probably been observed experimentally in bilayer systems with a weak tunnel coupling, in which the transversal electron motion does not destroy the in-plane coherence.[7–9] A key parameter defining a possible bilayer ground state is the space inversion symmetry. A method to determine experimentally the bilayer system symmetry is demonstrated in the present paper. The method utilizes an inelastic light scattering (ILS) response from dipole excitations in an in-plane magnetic field.

A symmetrically doped $Al_{0.33}Ga_{0.67}As/GaAs$ double quantum well heterostructure is used. The quantum well (QW) thicknesses are 200 Å, and QWs are separated by an $Al_{0.33}Ga_{0.67}As$ barrier of 25 Å thickness. The electron sheet densities ($n_{1,2}$) and mobilities in QWs are 3.6×10^{11} cm^{-2} and 1.8×10^{6} cm^2 V^{-1} s^{-1}, respectively. The QW confining potential curvature caused by the electric field from the charged donors creates a potential barrier additional to the one of the AlGaAs barrier, see Fig. 1. This reduces the tunneling gap to about 0.3 meV, which is much smaller than the electron Fermi energy. The heterostructure balancing is achieved by optodepleting one of the QWs with He-Ne laser light, which photon energy exceeds the fundamental gap in the AlGaAs barrier. Without an external magnetic field a detailed excitation spectrum of the structure studied is given elsewhere.[10] A Ti-sapphire laser tunable above the fundamental band gap in GaAs is used to excite the electron system. The excitation power density is about 0.1–1 W/cm^2. Measurements are performed in a cryostat with a horizontal split coil solenoid operating at 1.5 K. The light momentum transferred to the electron system through the ILS process [$\mathbf{q}=\mathbf{q}_i-\mathbf{q}_s$, where $\mathbf{q}_{i(s)}$ is incident (scattered) light momentum] is kept fixed at 1×10^{5} cm^{-1}. The scattered light is dis-

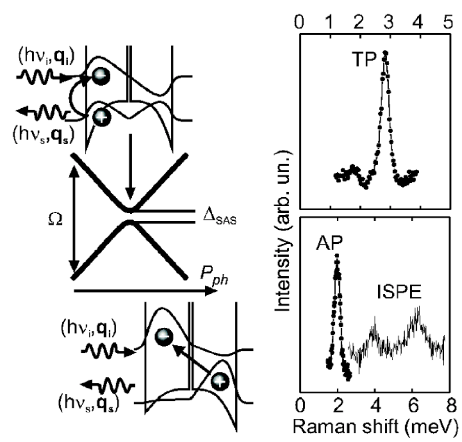

FIG. 1. Left, a sketch of the ILS process in a bilayer electron system in two states, symmetrical and asymmetrical. The electron wave function envelopes for the two lowest quantum subbands are shown by solid lines. A schematic dependence of the intersubband gap, Ω, on the depletion power is shown by a thick solid line. Right, an example of ILS spectra from a symmetrical (top) and asymmetrical (bottom) bilayer system measured at zero magnetic field. TP, AP, and ISPE are the tunnel plasmon, acoustical plasmon, and interlayer single particle excitations, respectively.

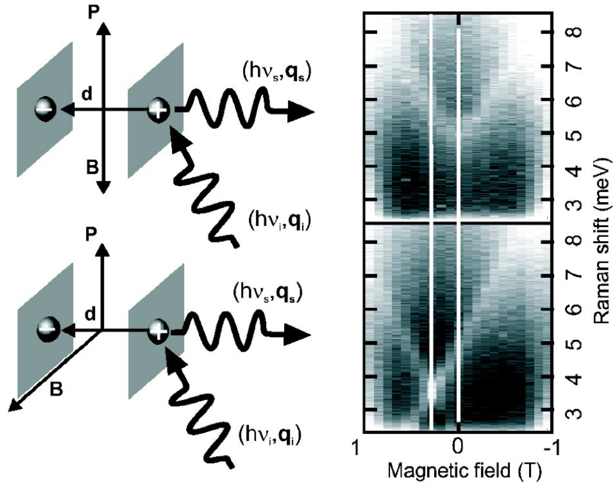

FIG. 2. Left, a sketch of the ILS process in an asymmetrical bilayer electron system in two experimental geometries with the light momentum parallel (top) and perpendicular (bottom) to an in-plane magnetic field. Right, corresponding experimental images of ILS resonances for interlayer single particle excitations. The degree of darkness is linearly proportional to the ILS signal intensity. The critical and zero magnetic fields are shown by white lines.

persed in a T-64000 triple spectrograph and is recorded with a charge coupled device camera. The experimental results from the double quantum well heterostructure are compared with those from a set of single asymmetrically doped QWs with thicknesses of 180, 220, 260, 300, and 400 Å with all of them having close densities of about 3×10^{11} cm^{-2}.

Figure 1 demonstrates typical ILS spectra of low lying neutral excitations taken in two bilayer states, symmetrical and asymmetrical. The state is regarded as asymmetrical when electron wave functions for two lowest quantum subbands are confined in separate layers, whereas a symmetrical state has wave functions located in both layers (see the diagram in Fig. 1). The ILS lines observed correspond to interlayer single particle excitations (ISPE) and antisymmetrical collective modes, an acoustical plasmon in the asymmetrical state (AP), and a tunnel plasmon in the symmetrical state (TP). In what follows, we will not consider collective modes, as they have been thoroughly discussed in Ref. 10, and will focus on interlayer single particle excitations. In accordance with energy-momentum conservation, single-particle excitations are allowed within the energy range $[\Omega-qv_F,\Omega+qv_F]$ with increased spectral weights at the boundaries, $\Omega\pm qv_F$, Fig. 1.[11]

Figure 2 shows an example of an ILS image measured from the bilayer system in the asymmetrical state at two magnetic field orientations, along and perpendicular to the light momentum, $\mathbf{q}$.[12] In the first case the excitation energies are symmetric, whereas in the second case they are nonsymmetric with the magnetic field inversion. The inversion anisotropy indicates the gauge energy term $1/c[\mathbf{d}\times\mathbf{B}]$.[4] We note that the interlayer excitations in asymmetrical double QWs possess a large dipole moment along the axis of separation between the layers. The dipole moment is given as

$$d = e|z_1 - z_2|, \tag{1}$$

where $z_1-z_2=\int dz\psi_1^*(z)z\psi_1(z)-\int dz\psi_2^*(z)z\psi_2(z)$ is the average distance between the excited electron in one layer and the hole left below the Fermi surface in the other (see the diagram in Fig. 1). Here, $\psi_{1,2}$ are transversal components of the wave function envelopes for the two lowest quantum subbands. Interaction of the electron system with the radiation field preserves vector $\mathbf{P}=\mathbf{\Pi}+1/c[\mathbf{d}\times\mathbf{B}]$, where $\mathbf{\Pi}$ is the kinematical momentum. The gauge term, $1/c[\mathbf{d}\times\mathbf{B}]$, arises from the Lorentz force acting on the electron and hole in separate layers. The kinetic energy of the excited electron depends on the kinematical momentum $\mathbf{\Pi}$:

$$E(\mathbf{\Pi}) = E\left(\left|\mathbf{P} - \frac{1}{c}[\mathbf{d}\times\mathbf{B}]\right|\right). \tag{2}$$

When the magnetic field satisfies to

$$\mathbf{P} = \frac{1}{c}[\mathbf{d}\times\mathbf{B}], \tag{3}$$

the kinetic energy is zero.

In agreement with the above equations, energies of single-particle excitations at the continuum boundaries change linearly with the magnetic field as $\Omega\pm qv_{F_1}+1/cdBv_{F_1}$ when $\mathbf{q}$ is parallel to $\mathbf{B}$, and as $\Omega\pm|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_1}$ when $\mathbf{q}$ is perpendicular to $\mathbf{B}$. Here, $v_{F_{1(2)}}$ is the Fermi velocity in a layer with larger (smaller) electron sheet density. At $\mathbf{q}\perp\mathbf{B}$ the kinetic energies for all single-particle excitations are zero at a *critical* magnetic field of 0.25 T, at which neither $\mathbf{q}$ nor $1/c[\mathbf{d}\times\mathbf{B}]$ is zero ($B=0$ and B critical are shown by white lines). Using the magnetic field value one finds from Eq. (3) the dipole moment for interlayer excitations of about 240 Å, which nearly coincides with the geometric center-to-center separation between QWs forming the bilayer system.

A modification of the excitation spectrum when the bilayer system is driven to a symmetrical state is shown in Fig. 3. It can be qualitatively understood if a nonrealistic model of two isolated QWs is imagined. As long as the intersubband gap Ω reduces the excitations energies reduce proportionally. The critical magnetic field (0.25 T) does not change, as the excitation dipole moment is constant. A nontrivial case occurs when the term, $|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_2}$, exceeds the intersubband gap Ω. Two excitation branches coexist. They are related to electron transitions from the first to the second quantum subband (**A**), $[\Omega-|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_1},\Omega+|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_1}]$, and from the second to the first quantum subband (**B**), $[0,-\Omega+|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_2}]$. Excitations from the two branches have equal but oppositely directed dipole moments, whereupon an increase in excitation energies from one branch in the magnetic field results in decreased energies from the other, and vise versa. At a certain value of system parameters, $\Omega<1/2(|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_2}-|\mathbf{q}-1/c[\mathbf{d}\times\mathbf{B}]|v_{F_1})$, the upper boundary of the **B** branch exceeds that of the **A** branch, which is the reason for *symmetrization* of the excitation spectrum, Fig. 3.

The above model describes virtual excitations between isolated layers. When a small tunnel coupling is introduced,

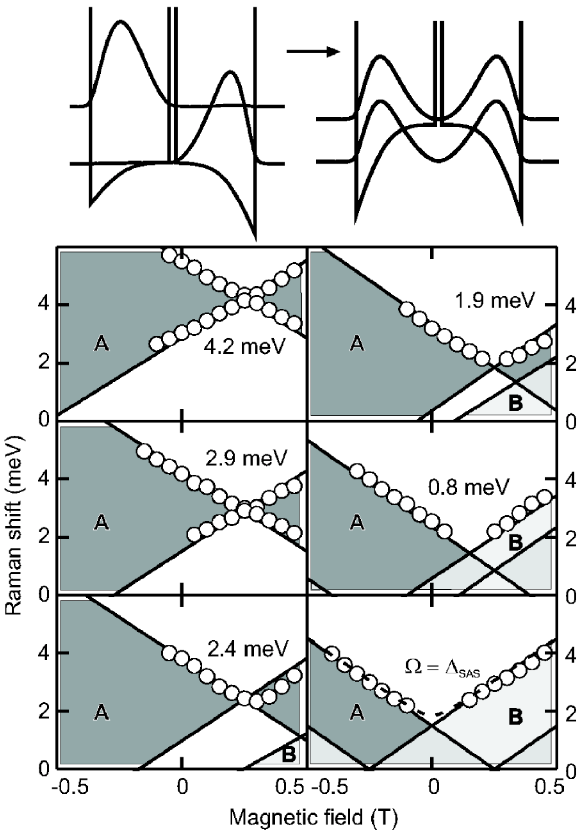

FIG. 3. Modification of the interlayer excitation spectrum when the bilayer system is driven from an asymmetrical to a symmetrical state. At the top, confining potential and squares of the electron wave functions in the two states are shown. The dark-colored shading corresponds to excitations from the first to the second quantum subband **A**, whereas the light-colored area designates excitations from the second to the first subband **B**. The experimental points are shown by white circles. The intersubband gap, Ω, is given. In the symmetrical state, $\Omega = \Delta_{SAS}$, a simulated within tunnel Hamiltonian upper excitation branch boundary is shown by a dashed line.

one finds that intersubband excitations in the symmetrical state do not have any dipole moment, see Fig. 3. Nevertheless, the excitation energies shift in the magnetic field as if the dipole moment existed, see Fig. 3. The shift is ascribed to the effect of in-plane magnetic field on the electron states in the system. It can be accounted for within a tunnel Hamiltonian approximation:[13,14]

$$H = \sum_{\mathbf{k}} \left[E^1_{\mathbf{k}}(B) a^+_{\mathbf{k}} a_{\mathbf{k}} + E^2_{\mathbf{k}}(B) b^+_{\mathbf{k}} b_{\mathbf{k}} - \frac{\Delta_{SAS}}{2}(a^+_{\mathbf{k}} b_{\mathbf{k}} + b^+_{\mathbf{k}} a_{\mathbf{k}}) \right]$$

$$= \sum_{\mathbf{k}} [\tilde{E}^1_{\mathbf{k}}(B) A^+_{\mathbf{k}} A^+_{\mathbf{k}} + \tilde{E}^2_{\mathbf{k}}(B) B^+_{\mathbf{k}} B_{\mathbf{k}}], \quad (4)$$

where

$$E^{1,2}_{\mathbf{k}}(B) = E_0 + \frac{\hbar^2}{2m}[(k_x \mp k_B)^2 + k_y^2].$$

$E^{1,2}$ are electron energies in QWs without tunnelling, Δ_{SAS} is the tunnel gap, $a^+_{\mathbf{k}}$, $a_{\mathbf{k}}$, $b^+_{\mathbf{k}}$, $b_{\mathbf{k}}$ are electron creation and annihilation operators in the two layers, E_0 is energy of the first quantized subband, $\mathbf{k}$ is the electron in-plane momentum, $k_B = a/l_B^2$, $2a$ is the distance between layer centers, l_B is the magnetic length, and $\mathbf{B} = (0, B, 0)$. A vector potential in the Landau gauge is used. The tunnel Hamiltonian approximation is valid if $E_0 \gg \Delta_{SAS}$. The electron energies in two lowest quantum subbands are

$$\tilde{E}^{1,2}_{\mathbf{k}}(B) = E_0 + \frac{\hbar^2}{2m}(k^2 + k_B^2) \pm \frac{1}{2}\sqrt{\left(\frac{2\hbar^2 k_x k_B}{m}\right)^2 + \Delta^2_{SAS}}, \quad (5)$$

and the corresponding wave functions are

$$\Psi_i = C^i_1 \psi_1(z) + C^i_2 \psi_2(z), \quad i = 1, 2,$$

$$C^i_1 = \frac{\Delta_{SAS}}{\sqrt{\Delta^2_{SAS} + 4[E^1_{\mathbf{k}}(B) - \tilde{E}^i_{\mathbf{k}}(B)]^2}}, \quad (6)$$

$$C^i_2 = \frac{2[E^1_{\mathbf{k}}(B) - \tilde{E}^i_{\mathbf{k}}(B)]}{\sqrt{\Delta^2_{SAS} + 4[E^1_{\mathbf{k}}(B) - \tilde{E}^i_{\mathbf{k}}(B)]^2}},$$

where $\psi_{1,2}(z)$ are transversal wave function components in the isolated layers. Depending on the in-plane momentum the electron wave functions are either unaffected by the magnetic field ($k_x = 0$) or totally transformed ($k = k_x$). The initially symmetrical and antisymmetrical wave functions become localized in separate layers when a small magnetic field (~ 0.2 T) is applied. The energies of single particle excitations with the in-plane momentum q along the x axis become:

$$E_{ISPE} = q v_{F_1} \cos(\mathbf{v}_{\mathbf{F}_1}, \mathbf{q}) + \sqrt{\left(\frac{2aeBv_{F_1}}{c}\right)^2 + \Delta^2_{SAS}}, \quad (7)$$

$q \ll k_F$, $k_B \ll k_F$. The single-particle exciatations form a continuum with density of states maxima at $\cos(\mathbf{k}_{\mathbf{F}_1}, \mathbf{q}) = \pm 1$. Taking $d = 2ae$ and $\Delta_{SAS} \ll dBv_{F_1}/c$ the continuum boundary energies are

$$E^{\pm}_{ISPE} \approx \left| \left(q \pm \frac{1}{c} dB \right) \right| v_{F_1}. \quad (8)$$

Thus, except for a small range of magnetic fields where $\Delta_{SAS} \sim dBv_{F_1}/c$, intersubband excitations in a tunnel coupled symmetrical bilayer system acquire a large dipole moment in an in-plane magnetic field and could be thought of as interlayer excitations. Two interlayer excitation branches, **A** and **B**, become coupled by tunneling. A critical magnetic field for energy minimum of the common brunch is not determined by Eq. (3) anymore, but is set at zero, see Fig. 3.

It is instructive to compare the critical magnetic field for bilayer and single layer systems as a function of a zero magnetic field dipole moment, see Fig. 4. The dipole moment is simulated as in Eq. (1) using electron wave function envelopes obtained self-consistently from one-dimensional Poisson and Schrödinger equations with respect to fit the known intersubband gap, Ω. In a single layer system the dipole moment reduces in QWs with a smaller QW width, Fig. 4. In the bilayer system the dipole moment reduces with the sys-

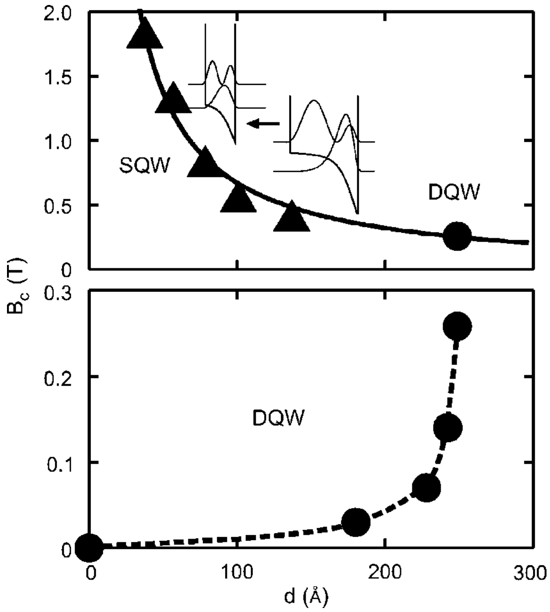

FIG. 4. Critical magnetic field vs dipole moment for single (triangles) and double (circles) QWs. The sketch shows squares of the wave function envelopes for two single QWs, 180 and 400 Å. The solid line is calculated from Eq. (3). The dashed line is a guide for the eyes.

tem symmetrization. Two systems, single layer and bilayer, differ by the influence of an in-plane magnetic field on electron states in two lowest quantum subbands. If in a bilayer system the magnetic field transforms the wave function envelopes, it affects negligibly those in a single layer. As a result, the critical magnetic field is inversely proportional to the dipole moment for a single layer system, which agrees well with Eq. (3), whereas it tends to zero when a bilayer system symmetrizes, see Fig. 4.

An ILS response from single particle excitations under in-plane magnetic field can be thus employed for determining a bilayer system symmetry. For example, an electron density unbalance of 3% in two layers transfers the system studied from a symmetrical to an asymmetrical state.[10] Due to such a small balancing range, the symmetrical state could hardly be established with a conventional magnetotransport balancing technique.[6] On the other hand, the excitation dipole moment is defined by a large interlayer distance, and has little to do with tunneling. To drive a bilayer system to a symmetrical state one has to supply a finite in-plane momentum to interlayer excitations via an ILS process and balance the system until the excitation energies become isotropic relative to the magnetic field inversion.

In conclusion, the effect of an in-plane magnetic field on the spectrum of interlayer excitations in a bilayer electron system with a weak tunnel coupling between the layers is studied. Excitation energies are found to depend linearly on the magnetic field due to the term $1/c[\mathbf{d}\times\mathbf{B}]$ in both symmetrical and asymmetrical states. A method to establish bilayer system symmetry is demonstrated.

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[1] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[2] A. Pinczuk, S. Schmitt-Rink, G. Danan, J. P. Valladares, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **63**, 1633 (1989).

[3] D. Gammon, B. V. Shanabrook, J. C. Ryan, D. S. Katzer, and M. J. Yang, Phys. Rev. Lett. **68**, 1884 (1992).

[4] L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, K. v. Klitzing, and K. Eberl, Phys. Rev. B **61**, 1712 (2000); L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, D. V. Kulakovskii, K. v. Klitzing, and K. Eberl, *ibid.* **66**, 073306 (2002).

[5] J. A. Simmons, S. K. Lyo, J. F. Klem, M. E. Sherwin, and J. R. Wendt, Phys. Rev. B **47**, 15 741 (1993); J. A. Simmons, S. K. Lyo, N. E. Harff, and J. F. Klem, Phys. Rev. Lett. **73**, 2256 (1994).

[6] N. E. Harff, J. A. Simmons, S. K. Lyo, J. F. Klem, G. S. Boebinger, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **55**, R13 405 (1997).

[7] For a review, see, *Perspectives in Quantum Hall Effect* edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1997).

[8] K. Muraki, T. Saku, and Y. Hirayama, Phys. Rev. Lett. **87**, 196801 (2001).

[9] I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **87**, 036803 (2001); M. Kellogg, J. P. Eisenstein, L. N. Pfeiffer and K. W. West, *ibid.* **93**, 036801 (2004).

[10] L. V. Kulik, S. V. Tovstonog, V. E. Kirpichev, I. V. Kukushkin, W. Dietsche, M. Hauser, and K. v. Klitzing, Phys. Rev. B **70**, 033304 (2004).

[11] J. K. Jain and S. Das Sarma, Phys. Rev. B **36**, 5949 (1987).

[12] The strongest resonances for the scattered light from the acoustical plasmon and from the inter-layer single particle excitations lie in different spectral ranges. To enhance the light intensity and to avoid a spectral overlap collective and single particle excitations we chose a spectral range where only single particle excitations are seen (Ref. 15). Laser excitation energies of 1.54 to 1.55 eV and of 1.57 to 1.59 eV are used to observe single particle and collective excitations, respectively.

[13] G. Gumbs and G. R. Aîzin, Phys. Rev. B **51**, 7074 (1995); G. R. Aîzin and G. Gumbs, *ibid.* **54**, 2049 (1996).

[14] A. A. Gorbatsevich and I. V. Tokatly, Semicond. Sci. Technol. **13**, 288 (1998).

[15] S. Das Sarma and D.-W. Wang, Phys. Rev. Lett. **83**, 816 (1999); D.-W. Wang and S. Das Sarma, Phys. Rev. B **65**, 125322 (2002).