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Localization at high magnetic fields in $GaAs/Al_xGa_{1-x}As$ quantum wires

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A low-temperature ($0.03 < T < 1.9$ K) magnetotransport study of $GaAs/Al_xGa_{1-x}As$ wires with a geometrical width $W_M < 400$ nm reveals substantial differences in the narrowing of Shubnikov-de Haas (SdH) oscillations in wires compared to two-dimensional (2D) $GaAs/Al_xGa_{1-x}As$. The data suggest that T-induced electronic localization, which is characterized by a power-law variation in the half width at half maximum of the SdH linewidth ($\Delta B \sim T^{0.4}$), occurs only on the low-energy side of the 1D Landau bands, while the high-energy side remains relatively unaffected, in sharp contrast to the 2D behavior. These results show that the transport properties of wires do not assume standard 2D characteristics even when $L_B = (\hbar/eB)^{1/2} < W$.

Transport studies at high magnetic fields, B, have pointed out the complex and unexpected interplay between localization and delocalization over the quantum Hall regime in quasi-two-dimensional (2D) systems,[1-4] where the variation of B, or the filling factor $\nu = hn/eB$, for a fixed electron density, n, induces a sequence of phase transitions between a dissipative state and integer quantum Hall states. The original expectations for complete localization in 2D systems (Ref. 5) were substantially changed by these experiments which demonstrated delocalization at high B and low temperatures, T. Recent technological advances have made possible a further reduction in dimensionality through the realization of quasi-one-dimensional (1D) structures in which characteristic length scales may approach or even exceed the electrical wire width, W.[6-8] Such structures have seen much recent interest since the restricted phase space in 1D promises higher speed devices compared to higher dimensions. At low T with $B \rightarrow 0$, the same feature is believed to produce violations of Ohm's law or 1D localization.[9,10] At high B, one expects the transport properties of quasi-1D structures to approach the usual 2D behavior when the magnetic length $l_B = (\hbar/eB)^{1/2} < W$. However, one may also argue for the breakdown of Hall quantization when W is sufficiently small such that one cannot identify localization in the confined direction. Indeed, experiment has already indicated certain modifications to the usual 2D behavior even in relatively wide (~ 10 μm) Hall bars.[4] Further reductions in W compared to characteristic length scales may therefore be expected to produce novel, high B (1D) localization phenomena in quasi-1D wires.

Here, we report the observation of a T-induced, asymmetric linewidth narrowing of the Shubnikov-de Haas (SdH) oscillations associated with the $N=0$ (spin down) and the $N=1$ Landau levels in 730-nm period, 400-nm-wide $GaAs/Al_xGa_{1-x}As$ wires prepared by optical (holographic) lithography. A comparison of these results with the standard 2D behavior suggests the absence of localization on the high-energy side of the Landau bands in wires. A simple model for the observed asymmetry is obtained upon taking into account the modification in the electronic spectrum due to confinement in parabolic quantum wells, and the localization of the low kinetic-energy states only, at the (1D) Landau band edge. Agreement between the experimental data and model predictions confirm that localization at high B in wires is unlike the known behavior of 2D systems: the localized states at the subband bottoms in wires are the edge states which collapse at the wire center when the width of a 2D sample "interior" is reduced to zero. Thus, SdH linewidth narrowing in wires is attributed to edge channel localization, unlike the 2D case, where the localization of bulk states is believed responsible for symmetric SdH narrowing. These results provide the first definitive evidence that high-field transport in wires differs from the usual behavior observed in 2D systems.

These $GaAs/Al_xGa_{1-x}As$ wires were fabricated from high-quality molecular-beam epitaxy prepared $GaAs/Al_xGa_{1-x}As$ heterostructures which were characterized by $n = 3\times10^{11}$ cm^{-2} and $\mu = 0.5\times10^6$ cm^2/Vs at $T = 4.2$ K. Holographic illumination was used to produce a photoresist wire grating with a period of 730 nm on the surface of the heterostructure.[11] Following photoresist development, the exposed trenches were plasma etched in order to produce large-area arrays of electronic wires at the $GaAs/Al_xGa_{1-x}As$ interface. For the sample examined here, the physical wire (mesa) width (400 nm) was somewhat larger than one-half the design-period (730 nm). However, carrier depletion resulting from the etch reduces the electrical wire width (130–200 nm) well below the mesa width (400 nm). Depletion widths ranging from 80 to 500 nm have been reported.[12,13] The lower estimate would indicate that the electrical width of the wires examined here is 240 nm, consistent with our studies which suggest that $W = 200$ nm.[14] Following wire preparation, alloyed Au-Ge/Ni contacts were fabricated and the low-T transport measurements were carried out in a He^3-He^4 refrigerator which allowed a working range spanning 0.03 K $< T < 1.9$ K and $B < 8$ T.

Figure 1 shows the two-terminal resistance of 98-μm-long wires, measured using standard ac lock-in techniques. The two-terminal resistance combines the series contact resistance, the diagonal (R_{xx}) resistance, and the off-diagonal resistances (R_{xy}). The contact resistance was determined to contribute negligibly to the measured resistance through $B = 0$, $T = 300$ K and $T = 1.5$ K studies which indicated that the resistance scaled as expected with the wire length. The relatively large length (98 μm)

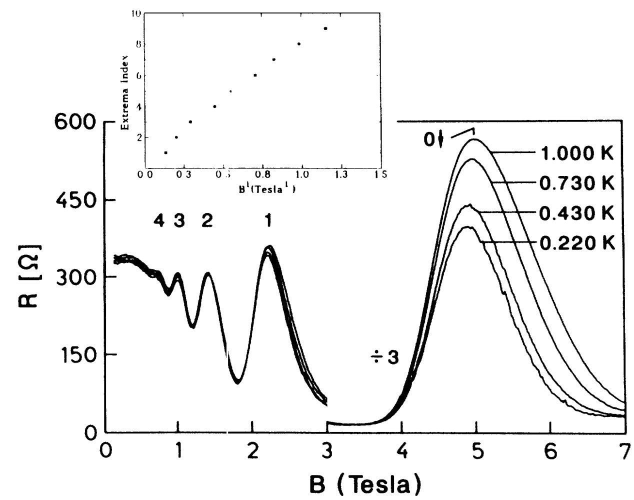

FIG. 1. A two-terminal resistance, R, is shown as a function of the magnetic field, B, in 730-nm period $GaAs/Al_xGa_{1-x}As$ wires. The electrical width of these 98-μm-long wires is estimated to be 0.2 μm. A half cycle plot is shown in the inset.

to width (0.2 μm) ratio ($\sim 4.9 \times 10^2$) of the wires enhances R_{xx} relative to R_{xy}. Thus, the measured signal reflects mostly the diagonal resistance, $R(B=0) \cong 85$ kΩ/wire, which will be discussed here. We note that a quantized value for the Hall resistance was assumed at $\nu=2$ in order to estimate the number of electrically active wires, $N_W=260$, in the sample. The data of Fig. 1 show SdH oscillations with increasing B and the SdH period indicates a 1D electron density $n \cong 3\times10^8$ m^{-1} ($\pm 15\%$). By correlating the measured resistance at $B=0$ with n and N_W, the electronic mean free path in the wires, $l \cong 1.4$ μm, was found to be comparable to l in the unprocessed material, $l \cong 4.8$ μm. The observation of SdH oscillations due to four spin degenerate Landau levels allows for an upper bound estimate of the confinement energy in these wires, $\hbar\omega_0 < 1.6$ meV. A plot of the extrema positions in B^{-1} versus integers exhibited some deviations from linearity (see inset Fig. 1).[6] The data were consistent with 0.5 meV $< \hbar\omega_0 <$ 1 meV, which is in agreement with previously reported values for $\hbar\omega_0$.[12] Thus, we estimate that the number of occupied 1D subbands spans the range $11 \gtrsim N_s \gtrsim 7$ at $B=0$. Note that $L_B < W$ even at the lowest B where SdH oscillations are observed. At $T=1.0$ K, the $N=0$ (down) SdH peak resistance per wire, $R \sim 450$ kΩ, exceeds the Hall resistance by an order of magnitude (see Fig. 1). The amplitude of SdH oscillations shows stronger T dependence with increasing B and the largest amplitude change is observed for the $N=0$ (spin-down) oscillation. In order to compare these results with the usual 2D behavior, the four terminal resistance of a Hall bar, fabricated from the same material, was also examined. Although the T dependence of the SdH amplitude showed qualitatively similar trends in the two systems, the variation of the linewidth with T showed dramatically different behavior. The novel high B, 1D localization effect may be identified as the narrowing of the SdH linewidth on the high-field side of the oscillation with decreasing temperatures while the low-field side is relatively unaffected by T (see Fig. 1). This behavior is most pronounced for the $N=0$ (spin-down) peak but it is also observable in the unsplit, $N=1$ SdH oscillation. In Fig. 2, we compare the T effect on the SdH linewidths by plotting the normalized resistance versus B for the two systems. For simplicity, the $N=1$ (down) peak has been shown for the 2D system since the $N=0$ (down) peak exhibited additional minima associated with fractional states at the lowest T. The figure demonstrates that the SdH linewidth in wires is virtually insensitive to T on the high-energy side of the oscillation, unlike the 2D case. This unusual feature reproduced in a series of samples with increasing length up to 120 μm.

Asymmetries in the shape of SdH oscillations in large aspect ratio, 2D samples have been examined by several groups.[15–21] It is usually observed that the lower-energy spin peak is reduced in amplitude with decreasing current or temperature, and the SdH oscillation assumes a characteristic sawtooth line shape.[15–18,20,21] In studies where edge current flow predominates, the reduction in the SdH amplitude is attributed to the electrical decoupling of the highest Landau level, which is responsible for dissipation, from the current carrying edge states of lower Landau levels.[17,20] Similar asymmetric reductions in the SdH amplitude have been observed in 2D samples doped with attractive and repulsive scattering centers,[18,19] and the effect has been attributed to a modification in the 2D density of states (DOS) due to the presence of the scattering centers.[19]

Here, we examine the origin of the asymmetric

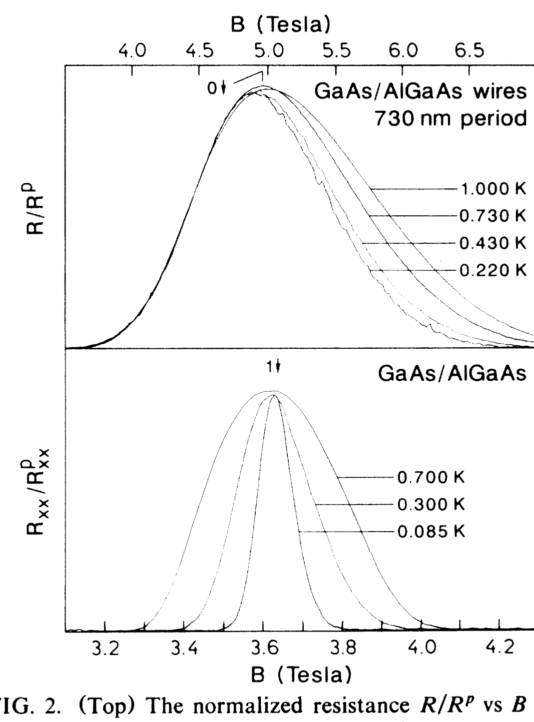

FIG. 2. (Top) The normalized resistance R/R^p vs B for the $N=0$ (down) SdH oscillation in $GaAs/Al_xGa_{1-x}As$ wires. (Bottom) The normalized four terminal resistance R_{xx}/R^p_{xx}, measured in a 2D $GaAs/Al_xGa_{1-x}As$ Hall bar, vs B for the $N=1$ (down) SdH oscillation. Note the asymmetric SdH linewidth narrowing with decreasing T in the wires. Normalization is carried out as in Refs. 3 and 4 for the 2D sample. For wires, a Hall signal was subtracted before normalization.

linewidth, as opposed to amplitude, suppression observed in wires. A qualitatively similar, T-driven linewidth narrowing has been examined in studies of transport scaling at high magnetic fields in 2D systems.[3,4] In these studies, SdH linewidth narrowing is attributed to the localization of electronic states in the tails of the disorder broadened δ-function-like 2D Landau level due to the progressive increase in the Thouless length, with reduced T, relative to the energy dependent localization length.[2-4,10] Observation of similar linewidth narrowing on the high-field side of the SdH oscillation, in wires and 2D systems, suggests that localization occurs on the low-energy side of Landau levels in the two cases. However, the temperature independent linewidth on the low-field side in wires is unlike the 2D result and it suggests the absence of localization on the high-energy side of the 1D subbands. These differences between the 2D and quasi-1D systems, even at high B where $l_B < W$, suggest that they reflect the modification in the electronic spectrum due to confinement, and phase coherence of electronic states in the confined direction, compared to regular 2D samples.

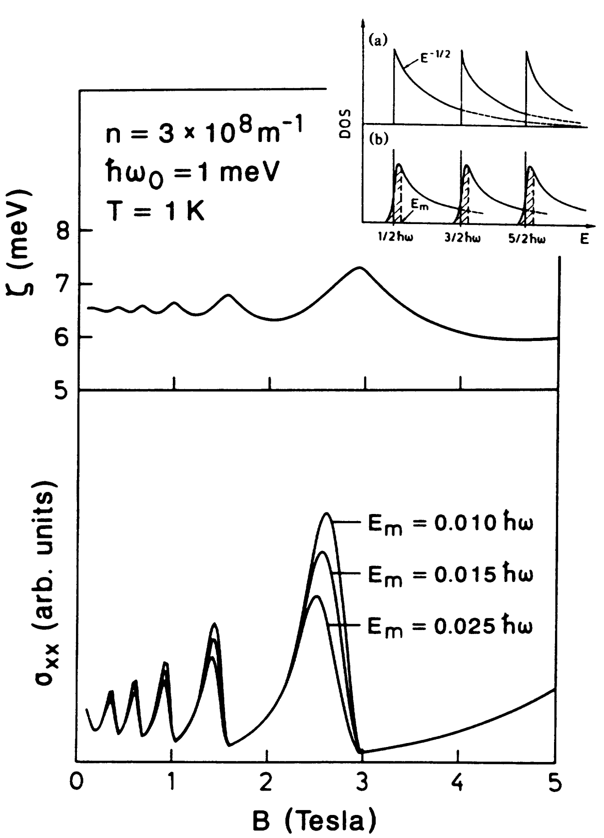

FIG. 3. Inset: (a) The ideal density of states (DOS) for quantum wires with parabolic confinement shows an $E^{-1/2}$ singularity at the subband bottoms. Here, E is the energy and $\hbar\omega$ is the subband spacing. (b) The model DOS suggested here for wires. E_m marks the mobility edge. (Top) The magnetic field variation of the Fermi level, ζ, calculated for the parameters $n=3\times10^8$ m^{-1}, $T=1$ K, $\hbar\omega_0=1$ meV. (Bottom) The diagonal conductivity, σ_{xx}, vs B for three values of E_m. Note that the narrowing of the SdH oscillations on the high-field side, with enhanced localization, is similar to the observed behavior in the data of Fig. 1.

Previous studies of quantum wires have indicated that their electronic properties may be adequately described by assuming a parabolic confining potential $V(x)=m^*\omega^2x^2/2$ with $\omega^2=\omega_0^2+\omega_c^2$.[8] Here, ω_0 defines the parabolic potential at $B=0$ and $\omega_c=eB/m^*$. The energy spectrum of this system for $B\geq0$ is $E_{n,k}(B)=(n+\frac{1}{2})\hbar\omega+\hbar^2k^2/2m^*(B)$ with $m^*(B)=m^*(1+\omega_c^2/\omega_0^2)$, while the DOS, $g(E)=(2\pi)^{-1}[2m^*(B)/\hbar^2]^{1/2}\times\sum[E-(n+\frac{1}{2})\hbar\omega]^{-1/2}$, exhibits an $E^{-1/2}$ singularity as in 3D systems at high magnetic fields [see Fig. 3, inset (a)].[22-24] Level broadening, due to finite scattering times,[25] would be expected to smear out the $E^{-1/2}$ singularity and produce a low-energy tail in the DOS below the Landau subbands.[22] In analogy with the 2D localization picture, one may invoke localization in the 1D subbands, where one expects localization to occur more readily with the disorder broadened, low kinetic-energy states (k) which lie near the band bottom. These localization effects may be examined using a model DOS which includes a mobility edge at the 1D-Landau subband bottom to separate quasilocalized states from the extended states in the 1D spectrum [see Fig. 3, inset (b)]. If one assumes negligible Landau level mixing then localized states and extended states associated with different Landau levels may possibly coexist at the same energy, and a mobility edge may be associated with each 1D subband.[21,24,26-28]

The magnetoresistance in wires has been studied using the simple picture of Fig. 3, inset (b), initially neglecting spin splitting since SdH narrowing is observed even when spin splitting is not resolved. The field variation of the Fermi level, ζ, is shown in Fig. 3 (top) for typical parameters $n=3\times10^8$ m^{-1}, $\hbar\omega_0=1$ meV, and $T=1.0$ K. At $B=0$, the conductivity reflects the diffusion constant, D, and the DOS at the Fermi level through $\sigma=e^2Dg(\zeta)$. As a similar relation holds for the diagonal conductivity σ_{xx},[22,29] the resistance at high fields ($\omega_c\tau>1$) reflects σ_{xx} and the variation of the DOS at the Fermi level through $R\sim\sigma_{xx}/\sigma_{xy}^2$. Thus, $R\sim\sigma_{xx}\sim g^2(\zeta)$.[22,29] In Fig. 3 (bottom), we have plotted $\sigma_{xx}\sim h(\zeta,T)=\int(-df/dE)\times g^2(E)dE$ where the integral counts only delocalized initial and final states in the vicinity of ζ, for three values of E_m. Here, $f(E)=[\exp(E-\zeta)/kT+1]^{-1}$. Note that an increase in the fraction of localized states per Landau subband results in an asymmetric narrowing of the oscillation on the high-field side, as observed in the data. Further numerical simulations which considered spin splitting and varying temperature, neglecting localization, did not show the asymmetric narrowing of SdH observed in the data, which confirmed that the observed SdH behavior is neither a simple spin splitting effect nor a smearing-of-the-Fermi-function effect. Thus, an enhancement of localization, with decreasing T, is necessary to reproduce the trends of the data. This behavior may be understood by noting the increase in the Thouless length with reduced T, $l_{\mathrm{Th}}\sim T^{-P/2}$,[10] which possibly results in the localization of progressively "longer," or higher in energy, states near the Landau level bottom at lower temperatures, in analogy with the picture for the T-induced localization of states in the Landau subband edges of 2D systems.[2-4] Such a model would suggest that the asymmetric SdH narrowing follows power-law variation with T reflecting $l_{\mathrm{Th}}\sim T^{-P/2}$,

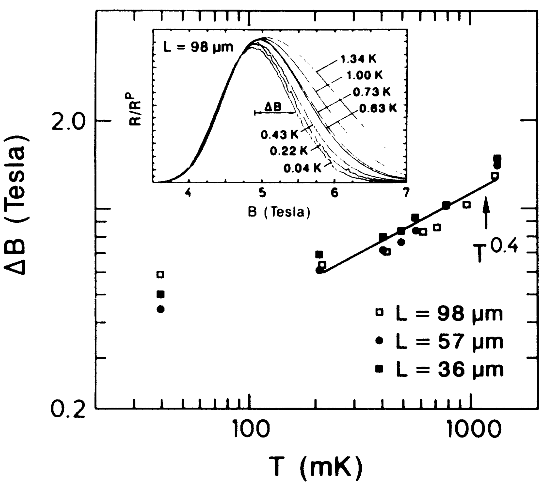

FIG. 4. The half width at half maximum (AB) on the high-field side of the SdH peak is shown vs T for three samples. The line is a fit to high-T data. Inset: The normalized resistance R/R^p vs B for the $N=0$ (down) SdH oscillations.

as observed in scaling studies of transport in the (2D) integral quantum Hall effect regime.[3,4] However, in this case, the half width at half maximum (HWHM) on the high-field side of the SdH peak (ΔB) is the relevant parameter for "scaling," and not the full width at half maximum as in 2D systems, because of the asymmetric localization in wires. In Fig. 4, we have shown the T dependence of the HWHM on the high-field side of the $N=0$ (down) peak, for three samples with differing lengths. A fit to the high-T data in the figure suggests that $\Delta B \sim T^{\kappa}$ with $\kappa=0.4$ ($\pm 30\%$), which agrees with a value reported for 2D systems (InGaAs/InP) with short-range scattering.[3]

Finally, the 2D limit may be approached by including a "flat" bottom, of width W', in the confining potential.[28] Such deviations from parabolicity would provide an extra disorder broadened peak in the DOS at the Landau level bottoms. In the presence of random disorder, the eigenstates of the 2DEG would exhibit an energy-dependent localization length which is symmetric about the peak 2D DOS.[3] The emergence of an extended state within the 2D DOS with increasing W' would eventually destroy the high-field SDH linewidth asymmetry observed in our studies of wires. Then, the high-energy tail in the 1D DOS (see Fig. 3, inset) may be identified with edge states.[26] Although our results only describe the narrowest wires, they suggest that the lowest-energy edge states of a given Landau level could be susceptible to Anderson localization even in wide 2D samples, if the bulk states of the Landau level are effective in mixing states of a given Landau level at opposite sample edges. If such a mechanism occurs in 2D samples, then the T-induced Anderson localization of edge states could play a role in the apparent decoupling of highest Landau level with reduced T.[20]

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[1]K. v. Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
[2]*The Quantum Hall Effect*, edited by R. E. Prange and S. M. Girvin (Springer, New York, 1987); H. Aoki, Rep. Prog. Phys. **50**, 655 (1987).
[3]H. P. Wei *et al.*, Phys. Rev. Lett. **61**, 1294 (1988); A. M. M. Pruisken, *ibid.* **61**, 1297 (1988).
[4]S. Koch *et al.*, Phys. Rev. Lett. **67**, 883 (1991).
[5]E. Abrahams *et al.*, Phys. Rev. Lett. **42**, 673 (1979).
[6]K. F. Berggren *et al.*, Phys. Rev. Lett. **57**, 1769 (1986).
[7]T. J. Thornton *et al.*, Phys. Rev. Lett. **63**, 2128 (1989); C. J. B. Ford *et al.*, *ibid.* **62**, 2724 (1989).
[8]D. Heitmann *et al.*, in *Proceedings of the 20th International Conference on the Physics of Semiconductors, Thessaloniki, Greece, 1990,* edited by E. M Anastassakis and J. D Joannopoulis (World Scientific, Singapore, 1991), Vol. 1, p. 13; T. Demel, D. Heitmann, and K. Ploog, Phys. Rev. Lett. **66**, 2657 (1991).
[9]D. J. Thouless, Phys. Rev. Lett. **39**, 1167 (1977).
[10]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[11]P. Grambow *et al.*, Microelect. Eng. **11**, 47 (1990).
[12]T. Demel *et al.*, Appl. Phys. Lett. **53**, 2176 (1988).
[13]K. K. Choi, D. C. Tsui, and K. Alavi, Appl. Phys. Lett. **50**, 110 (1987).
[14]R. G. Mani and K. v. Klitzing (unpublished).
[15]K. v. Klitzing *et al.*, in *Proceedings of the 17th International Conference on the Physics of Semiconductors, San Francisco, 1984,* edited by J. D. Chadi and W. A. Harrison (Springer-Verlag, New York, 1985), p. 271.
[16]H. Z. Zheng *et al.*, Phys. Rev. Lett. **55**, 1144 (1985).
[17]B. E. Kane, D. C. Tsui, and G. Weimann, Phys. Rev. Lett. **59**, 1353 (1987).
[18]R. J. Haug, K. v. Klitzing, and K. Ploog, Phys. Rev. B **35**, 5933 (1987).
[19]R. J. Haug *et al.*, Phys. Rev. Lett. **59**, 1349 (1987).
[20]B. W. Alphenaar *et al.*, Phys. Rev. Lett. **64**, 677 (1990).
[21]P. L. McEuen *et al.*, Phys. Rev. Lett. **64**, 2062 (1990).
[22]L. M. Roth and P. N. Argyres, in *Semiconductors and Semimetals,* edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. 1, p. 159.
[23]R. G. Mani, Phys. Rev. B **41**, 7922 (1990).
[24]O. Viehweger and K. B. Efetov, Phys. Rev. B **43**, 6840 (1991).
[25]R. G. Mani and J. R. Anderson, Phys. Rev. B **37**, 4299 (1988).
[26]M. Buttiker, Phys. Rev. B **38**, 9375 (1988).
[27]G. Müller *et al.*, Phys. Rev. B **42**, 7633 (1990).
[28]T. Ando, Phys. Rev. B **42**, 5626 (1990).
[29]T. Ando, J. Phys. Soc. Jpn. **36**, 1521 (1974).