Regimes of quantum transport in superlattices in a weak magnetic field

2004 J. Phys.: Condens. Matter 16 2447

(http://iopscience.iop.org/0953-8984/16/13/022)

Institute of Physics Publishing Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **16** (2004) 2447–2453 PII: S0953-8984(04)75539-3

Regimes of quantum transport in superlattices in a weak magnetic field

Yu A Pusep[1], **M B Ribeiro**[1], **H Arakaki**[1], **C A de Souza**[1], **P A Zanello**[1], **S Malzer**[2] **and G H Döhler**[2]

[1] Instituto de Fisica de São Carlos, Universidade de São Paulo, 13560-970 São Carlos, SP, Brazil
[2] Institut für Technische Physik I, Universität Erlangen, D-91058 Erlangen, Germany

Received 27 January 2004
Published 19 March 2004
Online at stacks.iop.org/JPhysCM/16/2447 (DOI: 10.1088/0953-8984/16/13/022)

Abstract

Weak field magnetoresistance was explored in GaAs/AlGaAs superlattices with different strengths of disorder produced either by the random variation of the well thicknesses or by the interface roughness. Depending on the disorder strength, three different regimes of the quantum transport were distinguished: the regimes of weak localization identified as the regimes of propagative and diffusive Fermi surfaces and the strongly localized insulating regime. Our results imply different dephasing mechanisms in the weak and strong localization limits. The vertical coupling energies in the superlattices determined with the random variation of the well thicknesses revealed a significant decrease with increasing disorder strength.

The semiconductor superlattices (SLs) present a great advantage for fabricating structures with desired electronic potentials and, thus, tailoring the dynamic electron properties. In the first proposal of superstructured materials [1] it was already mentioned that the controlled deviation from an ideal SL may provide a testing ground for theories of disordered systems. One of them, the most intriguing to date, is the localization theory. Weak disorder leads to a weak localization originating in the constructive quantum interference of time-reversed electron trajectories and this is well studied in metallic systems [2]. The weak localization is considered as a precursor of the strong localization [3], which results in the insulating state. By increasing the randomization strength a disorder induced metal-to-insulator transition (MIT) can be achieved. Localization can be obtained in the SLs with strong enough disorder when the localization energy of electrons dominates over their kinetic energy. Both of the relevant energies can be monitored by means of SL structural characteristics such as the width of the layers and their compositions.

An extensive investigation of the weak localization in SLs was performed in a series of articles [4–7], while the quantum interference effects were studied in the intermediate localization regime with $k_F l \approx 1$ (where k_F and l are the Fermi wavenumber and the mean free path length respectively) in short period GaAs/AlAs SLs [8, 9] where, however, no connection with the MIT was presented.

In this work we studied the electronic transport properties of intentionally disordered SLs where the disorder strength can be quantitatively controlled. The disorder was provided either by random variation of the well thicknesses or by the interface roughness. In order to characterize the type of transport (metallic or activation), we measured the temperature dependences of the resistances. Then, the weak field magnetoresistances were explored in different quantum transport regimes. The emphasis was on the investigation of a modification of the weak field magnetoresistance and the processes of quantum interference across the MIT.

Depending on the structure of a SL, three different regimes of quantum transport can be distinguished. There are two weak localization regimes (in the notation of [10]), when $k_F l > 1$:

(i) the propagative Fermi surface (PFS) regime when $t_z \tau > \hbar$ (with t_z and τ being the vertical coupling energy, which in a regular SL is equal to the miniband width, and the elastic scattering time respectively) and
(ii) the diffusive Fermi surface (DFS) one, when $t_z \tau < \hbar$,

and a regime of strong localization, with $k_F l < 1$, when the wavenumber of the electrons is not well determined. The DFS transport regime corresponds to the quasi-two-dimensional electron system formed in a SL with an open Fermi surface. The vertical disorder decreasing the vertical coupling energy also favours the DFS regime.

In a weak magnetic field orthogonal to the plane of the layers the weak localization corrections to the parallel conductivity are determined by the following expressions. In the PFS regime [4]

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

and in the DFS regime [10]

$$\Delta\sigma_{\mathrm{DFS}}(H) = -\frac{e^2}{2\pi^2\hbar d_{\mathrm{SL}}} F(\delta, \delta') \tag{2}$$

where $a = \sqrt{D_\parallel / D_z}$ is the coefficient of anisotropy, with $D_\parallel$ and D_z being the diffusion coefficients parallel and perpendicular to the layers respectively, $l_{\mathrm{H}} = \sqrt{\hbar/eH}$ is the magnetic length and the functions $F(\delta)$ and $F(\delta, \delta')$ are given in the corresponding references. The arguments of these functions are $\delta = \frac{l_{\mathrm{H}}^2}{4D_\parallel \tau_\varphi}$ and $\delta' = \frac{l_{\mathrm{H}}^2}{4D_\parallel}(\frac{1}{\tau_\varphi} + \frac{2}{\tau_0})$, where τ_φ is the phase-breaking time and $\tau_0 = \frac{\hbar^2}{t_z^2 \tau}$ is the time an electron needs to change a layer. Thus, two characteristic times (τ_φ and τ_0) determine the DFS regime and the relationship between them establishes the transport regime coherence of a SL. In the coherent regime, when $\tau_\varphi > \tau_0$ an electron coherently changes plane, while in the incoherent regime when $\tau_\varphi < \tau_0$ the SL behaves as a set of independent planes.

On the other hand, at strong disorder ($k_F l \lesssim 1$) and in a weak magnetic field the self-consistent approach gives [11]

$$\Delta\sigma(H) = \frac{e^2 \delta^{-3/2}}{192\pi^2\hbar\alpha l_{\mathrm{H}}}. \tag{3}$$

In this case the quantum correction arises from interference between the probability amplitudes for direct hopping transitions involving the localized states emerging due to disorder.

The samples studied here were $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ SLs (where the thickness of the layers is expressed in monolayers, ML) grown by molecular beam epitaxy on semi-insulating (001) GaAs substrates. In order to form the degenerate electron system all the samples were

Table 1. Parameters measured at $T = 1.6$ K for the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with random variation of the well thickness.

δ_{SL}	n_H (cm^{-3})	μ_H (cm^2 V^{-1} s^{-1})	$k_F l$	τ_0 (ps)	t_z (meV)
0.35	1.3×10^{18}	1657	11.9	1.8	1.9
0.59	1.2×10^{18}	1710	12.5	2.1	1.8
0.82	1.2×10^{18}	1977	14.2	2.9	1.4
1.13	9.9×10^{17}	2037	12.0	2.5	1.5

Table 2. Parameters measured at $T = 1.6$ K for the periodic $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with different well thicknesses.

m (ML)	n_H (cm^{-3})	μ_H (cm^2 V^{-1} s^{-1})	$k_F l$	τ_φ (ps)
150	5.1×10^{17}	2513	10.2	506
50	8.3×10^{17}	2500	8.8	385
30	3.4×10^{17}	1027	2.1	110
15	7.1×10^{16}	446	0.42	35
10	1.0×10^{17}	64	0.084	48

homogeneously doped with Si. The vertical disorder was introduced by a random variation of the well thicknesses (m) around the nominal value 17 ML. In this case the disorder strength was characterized by the disorder parameter $\delta_{SL} = \Delta / W$, where Δ is the full width at half-maximum of a Gaussian distribution of the electron energy calculated in the isolated quantum well and W is the miniband width of the nominal SL in the absence of disorder. However, the disorder driven MIT could not be obtained in parallel transport for these SLs because of the suppression of the disordered superlattice potential due to the effect of the vertical screening. As a result, when increasing disorder, instead of being localized the electrons become redistributed over the vertical random potential, increasing both the local Fermi energy and, consequently, the effective parallel mobility [13]. The nominal dopings of these SLs were 1.2×10^{18} cm^{-3} which resulted in an open Fermi surface and, consequently, in quasi-two-dimensional electron systems where the DFS transport regime is expected [14].

The strong localization was achieved in short period regular $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ SLs where the disorder was provided by the interface roughness. The scattering due to the interface roughness strongly increases with decreasing well thicknesses [12] forcing the electrons into localized states when $k_F l < 1$ and, thus, resulting in an insulating regime. A variation of the thicknesses of the GaAs wells in the range 10–150 ML produced the disorder driven MIT. The relatively low nominal doping of these periodic SLs caused a closed Fermi surface, exhibiting three-dimensional transport character.

Parallel transport measurements were performed using the standard four-probe low frequency (5 Hz) lock-in technique in a pumped liquid He cryostat in a magnetic field directed perpendicular to the layers at temperatures of 1.6–15 K. The electronic characteristics of the SLs studied here are presented in tables 1 and 2. The mobilities and the values of $k_F l$ obtained for all the samples studied here are depicted in figure 1 as functions of the disorder parameters: the vertical disorder strength δ_{SL} and the thickness of GaAs layers in the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with random variation of the well thicknesses and with fixed different well thicknesses respectively. According to these data the interface roughness dominates the electron scattering at well thicknesses smaller than 50 ML and the $k_F l$ values indicate that the insulating regime occurs in the short period SLs with well thicknesses smaller than 20 ML.

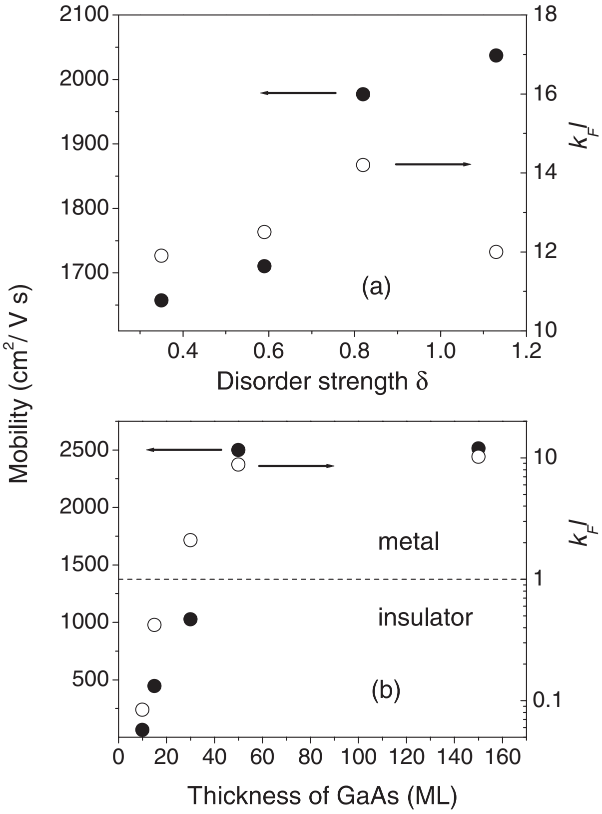

Figure 1. The Hall mobilities (closed circles) and the values of $k_F l$ (open circles) obtained at $T = 1.6$ K for the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with random variation of the well thicknesses (a) and with fixed different well thicknesses (b).

The Hall data also show that the weak field condition $\omega_c\tau \ll 1$ holds for all of the samples at the magnetic field used (0.5 T). Therefore, no negative magnetoresistance due to the electron–electron interaction effects is anticipated. The estimation of the appropriate characteristic magnetic fields [2] shows that the spin–orbital effects do not contribute to the magnetoresistances studied here. In all the aperiodic SLs one finds DFS coherent regimes. The PFS regime arise in periodic SLs with wide wells ($m = 150$, 50 and 30 ML), while the SLs with the well thicknesses $m = 15$ and 10 ML revealed insulating behaviour, proved by the values of $k_F l$ being smaller than one and by the exponential decreases of the resistance with the temperature. The decrease of the Hall electron concentration found with increase of the disorder strength is an additional manifestation of the localization of the conduction electrons.

In the weak localization regime the perturbative theory predicts for the conductivity of the three-dimensional Fermi system [2]

$$\sigma = \sigma_0 - \frac{e^2}{\hbar\pi^3}\left(\frac{1}{l} - \frac{1}{L_\varphi}\right) \qquad (4)$$

where σ_0 is the residual conductivity and at low temperatures the dependence of the conductivity on the temperature is due to the temperature variation of the phase-breaking length $L_\varphi = aT^{-p/2}$ with p being an index depending on the scattering mechanism. Consequently,

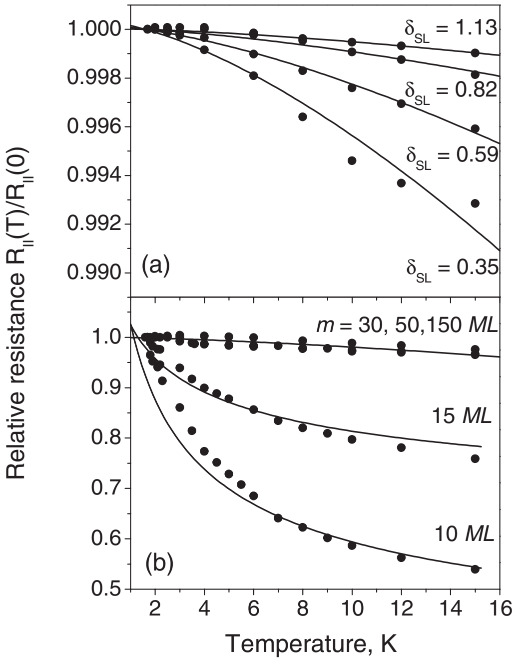

Figure 2. The temperature behaviour of the relative parallel resistances measured in the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with random variation of the well thicknesses (a) and with different fixed well thicknesses (b). The full curves are the relative resistances calculated according to equation (5) except those corresponding to the superlattices with $m = 10$ and 15 ML, which were computed with equation (6).

with increasing temperature the conductivity should slowly increase due to the temperature destruction of the phase coherency:

$$\sigma(T) = \sigma_0 + \frac{e^2}{\hbar\pi^3 a} T^{p/2}. \tag{5}$$

The temperature dependences of the resistances measured in the SLs with the vertical intentional disorder are depicted in figure 2(a). They show a weak decrease with increasing temperature exhibiting the expected metallic behaviour. The resistances calculated by equation (5) for the electron–phonon inelastic scattering ($p = 3$), shown in figure 2(a) by solid curves, demonstrate good agreement with the experimental data.

In the weak localization metallic regime $L_\varphi \gg l$ and, therefore, the dependence of the quantum correction of the conductivity on the disorder strength (the second term in equation (4)) is determined by the elastic scattering length l. Therefore, the decrease of the quantum correction observed with increasing disorder in figure 2(a) is consistent with the corresponding increase of the mobility.

The temperature dependences of the resistances measured in the periodic SLs with relatively thick wells ($m = 30$, 50 and 150 ML) shown in figure 2(b) also displayed a similar metallic behaviour.

Deep in the localized regime found in the periodic SLs with thicknesses of the wells $m = 10$ and 15 ML the resistances showed an activation type exponential decrease with the temperature [15]. The curves in figure 2(b) corresponding to these SLs show the resistivities

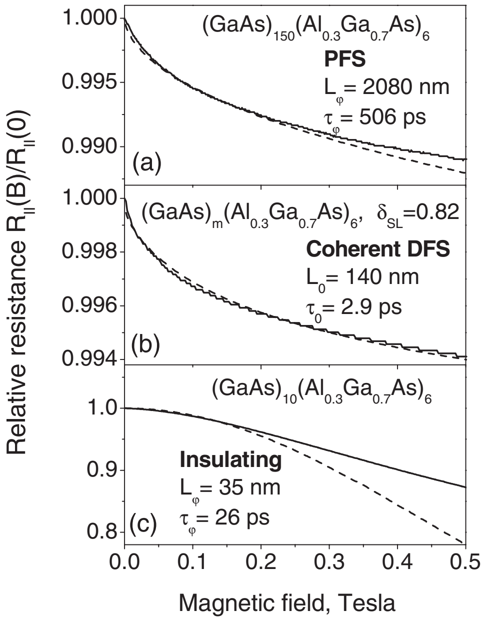

Figure 3. Weak field relative parallel magnetoresistances measured at $T = 1.6$ K in $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with different transport regimes: (a) propagative Fermi surface, (b) diffusive Fermi surface and (c) insulating regime. The broken curves were calculated as explained in the text.

calculated according to the Mott's law for variable-range hopping:

$$\rho(T) = \rho_0 \exp\left[\left(\frac{T_0}{T}\right)^{1/4}\right] \tag{6}$$

where T_0 is the characteristic temperature. The best fits were obtained with $T_0 = 7.8$ and 0.25 K for the SLs with $m = 10$ and 15 ML respectively.

The weak field magnetoresistance traces obtained in all of the relevant transport regimes are depicted in figure 3. It is worth mentioning that the concavity of the magnetoresistance changes sign when passing the metal-to-insulator transition; in both metallic regimes (PFS and DFS) it is positive, while it becomes negative in the insulating regime. The experimental data were compared with the magnetoresistances calculated according to equations (1)–(3). The best fits were obtained with the parameters collected in tables 1, 2. The results of the fittings are demonstrated in figure 3 for selected SLs by dashed curves. In the DFS regime we were able to determine the time an electron needs to change a layer (τ_0), which indeed was found to be much shorter than the dephasing time, thus confirming the coherency of this regime. Our data show that with increasing vertical disorder an electron needs a longer time to change a layer. This happens because the increasing vertical disorder reduces the vertical tunnelling rate. In fact, the calculated values of the vertical coupling energy t_z shown in table 1 revealed a decrease with the increasing vertical disorder strength (δ).

The values of the phase coherent lengths (L_φ) and the dephasing times (τ_φ) were found to be much bigger in the metallic (PFS) regime than in the insulating one. This possibly indicates different dephasing mechanisms in these regimes. The dependence of the phase-breaking time on the elastic scattering time obtained in the periodic SLs with different well thicknesses is depicted in figure 4. It also demonstrates different dephasing mechanisms. The dephasing times measured in the metallic SLs (with the thicknesses of GaAs 150, 50 and

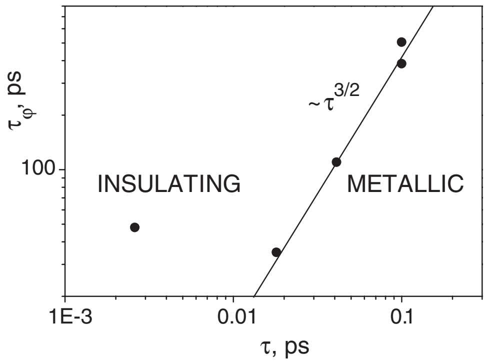

Figure 4. The dependence of the phase-breaking time τ_φ on the elastic scattering time τ obtained at $T = 1.6$ K in periodic superlattices with different well thicknesses.

30 ML) may be well fitted with the dependence $\tau_\varphi \sim \tau^{3/2}$. As was found in [16], such a dependence corresponds to the decoherence due to the electron–electron interaction in the presence of disorder, whereas in the insulating case (SL with 10 ML of GaAs) we found strong enhancement of the phase-breaking time. Indeed, the scaling theory predicts such an increase of the inelastic effects close to the metal–insulator transition [17].

In conclusion, we would like to emphasize that the investigation of the weak field magnetoresistance was performed in intentionally disordered superlattices with different strengths of the disorder exhibiting both metallic and insulating behaviour. Depending on the disorder strength, different quantum transport regimes were realized. The experimental results were compared with the corresponding theories and the characteristic parameters of the quantum interference were determined. We observed a significant alteration of the dephasing mechanism responsible for the quantum interference when passing from metal to insulating transport regimes. The vertical coupling energy, which controls the quantum interference in the SLs in the DFS regime, was found to decrease with increasing vertical disorder strength.

Acknowledgment

Financial support from FAPESP is gratefully acknowledged.

References

[1] Esaki L and Tsu R 1970 *IBM J. Res. Dev.* **14** 61
[2] Lee P A and Ramakrishnan T V 1985 *Rev. Mod. Phys.* **57** 287
[3] Bergmann G 1984 *Phys. Rep.* **107** 1
[4] Szott W, Jedrzejek C and Kirk W P 1989 *Phys. Rev.* B **40** 1790
[5] Szott W, Jedrzejek C and Kirk W P 1989 *Phys. Rev. Lett.* **18** 1980
[6] Szott W, Jedrzejek C and Kirk W P 1992 *Phys. Rev.* B **45** 3565
[7] Szott W, Jedrzejek C and Kirk W P 1993 *Phys. Rev.* B **48** 8963
[8] Gougam A B, Sicart J and Robert J L 1997 *J. Physique* III **7** 133
[9] Gougam A B, Sicart J, Robert J L and Etienne B 1999 *Phys. Rev.* B **59** 15308
[10] Cassam-Chenai A and Mailly D 1995 *Phys. Rev.* B **52** 1984
[11] Bryksin V V and Kleinert P 1996 *Z. Phys.* B **101** 91
[12] Sakaki H, Noda T, Hirakawa K, Tanaka M and Matsusue T 1987 *Appl. Phys. Lett.* **51** 1934
[13] Pusep Yu A, Chiquito A J, Mergulhão S and Toropov A I 2002 *J. Appl. Phys.* **92** 3830
[14] Chiquito A J, Pusep Yu A, Gusev G M and Toropov A I 2002 *Phys. Rev.* B **66** 035323
[15] Schklovskii B I and Efros A L 1984 *Electron Properties of Doped Semiconductors* (Berlin: Springer)
[16] Altshuler B L and Aronov A G 1979 *JETP Lett.* **30** 482
[17] Castellani C, DiCastro C, Kotliar G and Lee P A 1986 *Phys. Rev. Lett.* **56** 1179