Electron dephasing scattering rate in two-dimensional GaAs/InGaAs heterostructures with embedded InAs quantum dots

I. R. Pagnossin,[1] A. K. Meikap,[2,a)] A. A. Quivy,[1] and G. M. Gusev[1]
[1]*Institute of Physics, University of São Paulo, CP 66318, São Paulo 05315-970, SP, Brazil*
[2]*Department of Physics, National Institute of Technology, Durgapur-713209, W.B., India*

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We report a comprehensive study of weak-localization and electron-electron interaction effects in a GaAs/InGaAs two-dimensional electron system with nearby InAs quantum dots, using measurements of the electrical conductivity with and without magnetic field. Although both the effects introduce temperature dependent corrections to the zero magnetic field conductivity at low temperatures, the magnetic field dependence of conductivity is dominated by the weak-localization correction. We observed that the electron dephasing scattering rate τ_φ^{-1}, obtained from the magnetoconductivity data, is enhanced by introducing quantum dots in the structure, as expected, and obeys a linear dependence on the temperature and elastic mean free path, which is against the Fermi-liquid model. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2996034]

I. INTRODUCTION

During the past few decades, both theoretical[1–4] and experimental[5–8] investigations of the low temperature electrical conductivity of a weakly disordered electronic system have led to quantum corrections to the classical Boltzmann contribution. This work has been extended to high mobility two-dimensional electron gas (2DEG) systems during the last decade.[9–13] For two-dimensional electron systems (2DES) at low temperature (T) and zero magnetic field (B), the electrical conductivity decreases logarithmically with T. This nonclassical aspect of the carrier transport has been theoretically interpreted by two distinct mechanisms: the weak-localization (WL) and the electron-electron interaction (EEI). The former arises from quantum interference between waves propagating along the same path but in opposite directions. In the presence of weak magnetic fields, the electron waves traveling along a path in two opposite directions pick up a phase difference, which destroys the initial phase coherence. As a result, we have positive magnetoconductance (i.e., negative magnetoresistance). Moreover, the interference is also destroyed by other processes, like inelastic and spin-orbit scatterings, because these relaxation times are comparable to the time for breaking the phase of the wave function. A finite spin-orbit coupling introduces random deviations between the spin states of electrons that are backscattered on time reversed paths. The resulting spin-space average suppresses the quantum correction to the conductance and changes its sign, giving rise to weak antilocalization, the manifestation of which is a negative magnetoconductance with an antilocalization peak at very low magnetic field.

Therefore, the WL theory yields information about the relaxation times of the electron phase and spin. It can also be a very effective tool for studying the various electron scattering times. It is now established that by using WL effect, analysis of the low field magnetoconductivity may provide quantitative information of the dephasing (τ_φ) and spin-orbit (τ_{so}) scattering times for the electron waves in highly mobile 2DEG gas systems.

Due to rapid developed of spintronics, dealing with the manipulation of spin in electronic devices, the spin properties of semiconductor quantum wells (QWs) and other heterostructures have aroused widespread interest among the investigators, mainly the spin-orbit interaction.[14–19] On the other hand, τ_φ is a quantity of great importance for the analysis of the transport in semiconductor samples, because it sets the scale of the transition between quantum and classical behaviors. Also, it provides information about the microscopic interactions among electrons and among electrons and phonons. But there is still dearth for systematic study on the electron dephasing relaxation of these highly mobile 2DES. Therefore, the dependence of the electron scattering times on temperature and on elastic mean free path (l_e) is crucial to a profound understanding of the underlying dynamics of the inelastic electron scattering.

In the present article, we report the details of electrical transport properties study in the light of WL and EEI effects in GaAs/InGaAs heterostructures with nearby InAs quantum dots (QDs). The dephasing scattering time (τ_φ) has been determined by comparing the low field magnetoconductivity to the WL theoretical predictions. Our results for the temperature and electron mean free path dependences of τ_φ are described below.

II. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

The sample structure designed for this study consists of the following layers grown sequentially from bottom to top on a GaAs(001) substrate after oxide desorption: first, a 50 nm thick GaAs layer was grown, followed by a $10 \times (AlAs)_5(GaAs)_{10}$ superlattice and a 200 nm thick GaAs layer. We then deposited a silicon (Si) layer with a nominal concentration 4×10^{12}, a 7 nm thick GaAs back spacer, a 10 nm wide $In_{0.16}Ga_{0.84}As$ channel, a 8 nm thick GaAs top

a)Electronic mail: meikapnitd@yahoo.com.

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spacer, an InAs layer with a (nominal) thickness d_{InAs}, a 50 nm thick GaAs layer, and a 10 nm thick Si-doped GaAs cap layer. A set of five samples was grown with a different value of d_{InAs} from sample to sample: 1.0, 1.5, 1.75, 2.0, and 2.5 monolayer (ML). In the rest of the text, each sample will be designated by the nominal thickness d_{InAs} of its InAs layer. *Ex situ* atomic-force microscopy measurements were performed on a control sample similar to the sample with $d_{\mathrm{InAs}}=2.5$ ML but where no material was further deposited after the growth of the InAs layer. It is found that, under our growth conditions, the QD density in that sample was around 4×10^{10} cm^{-2} and the structures had an average height and diameter of 5 and 20 nm, respectively. Note that, in our sample structure, the InAs QDs were grown after the GaAs/InGaAs QW. Hence, the intrinsic quality of our InGaAs channel is expected to be as good as the reference sample, which was grown without any InAs layer (referred here as $d_{\mathrm{InAs}}=0$ ML).

The samples were patterned with Hall bars (200×500 μm) and standard lock-in techniques were used (1 μA ac) in order to get the electron concentration and transport mobility by means of the Shubnikov–de Haas and ordinary Hall effects, respectively. The measurements were carried out in the temperature range $1.3\leq T\leq5$ K in a bath cryostat inserted in a superconducting coil.

III. RESULTS AND DISCUSSION

The electrical resistivity and magnetoconductivity of different samples have been measured in the temperature range $1.3\leq T\leq5$ K. At low temperature ($T<5$ K), an anomalous decrease in conductivity is observed with further lowering of temperature, which can be explained taking into consideration the effects of the weak-localization and electron-electron interaction. Including both the corrections, the total zero magnetic field conductivity of the system can be expressed as

$$\sigma_{xx}(T)=\sigma_{xx}(0)+\Delta\sigma_{\mathrm{WL}}(T)+\Delta\sigma_{\mathrm{EEI}}(T). \tag{1}$$

The first term is the classical Drude conductivity, while the second and third terms are corrections due to WL and EEI, respectively.

According to the theory of WL, the temperature dependence correction to the conductivity for 2DEGs in the diffusive region ($k_BT\tau/\hbar<1$) is given by[2,20,21]

$$\Delta\sigma_{\mathrm{WL}}(T)=(e^2/2\pi^2\hbar)\ \ \alpha p\ \ln[k_BT\tau/\hbar], \tag{2}$$

where k_B is the Boltzmann constant, τ is the elastic scattering time, p is the exponent in the temperature dependence of the inelastic scattering time ($\tau_\varphi\propto T^{-p}$), and $\alpha=1$ for weak spin-orbit scattering and $-\frac{1}{2}$ for strong spin-orbit scattering. On the other hand, the correction due to the interaction effect in the diffusive regime can be written as[22]

$$\Delta\sigma_{\mathrm{EEI}}(T)=(e^2/2\pi^2\hbar)\ \ \lambda\ \ln[k_BT\tau/\hbar], \tag{3}$$

where λ is the interaction constant.[23]

In order to find the contributions of WL and EEI corrections to the temperature dependence conductivity, first we have analyzed the data with WL contribution alone taking the value of $\alpha=1$ and $p=1$ (detailed later) and plotted in Fig. 1 as dashed line. It is observed from the figure that the theoretical values did not match the experimental data. Second, we have included the EEI contribution with the WL contribution and plotted in Fig. 1 as solid line. Hence the total contribution is in good agreement with the experimental data for $\lambda=-0.185$. In both the calculations $\sigma_{xx}(0)$ is taken as 1.16×10^{-3} (Ω^{-1}). Therefore, both the WL and EEI effects play a noticeable role to the low temperature conductivity in absence of magnetic field. As both Eqs. (2) and (3) present logarithmic temperature variation, Eq. (1) can be rewritten as $\sigma_{xx}(T)=\sigma_{xx}(0)+\gamma\ln[k_BT\tau/\hbar]$, with $\gamma=(e^2/2\pi^2\hbar)(\alpha p+\lambda)$. We have fitted the experimental data with this expression

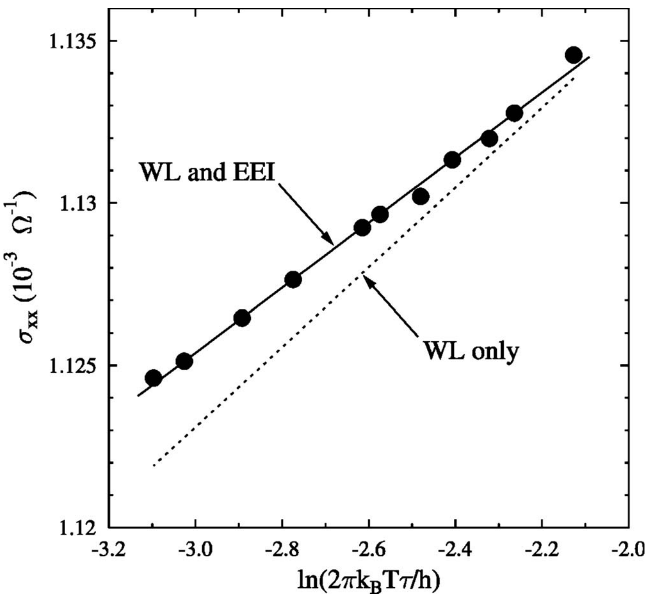

FIG. 1. Conductivity at $B=0$ T for the sample 1.75 ML.

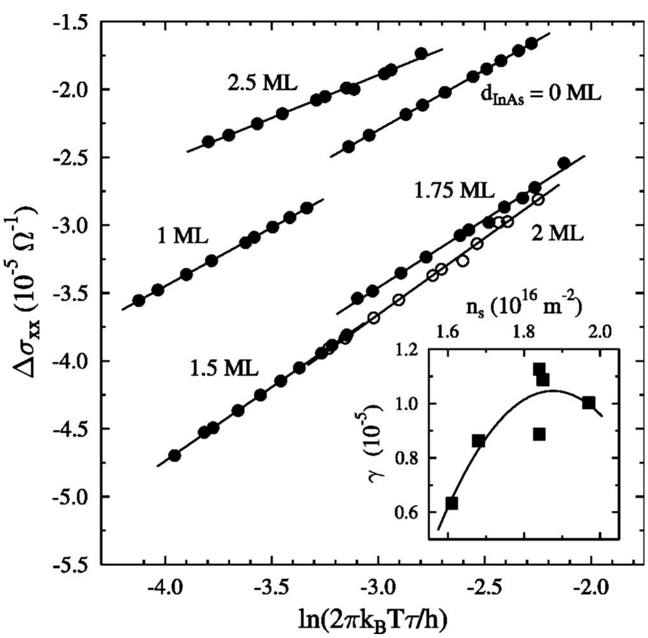

FIG. 2. Variation in conductivity change $\Delta\sigma_{xx}(T)$ as a function of temperature of various samples. The inset shows slope γ as a function of the carrier concentration.

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taking $\sigma_{xx}(0)$ and γ as the fitting parameters. Figure 2 shows the variation in conductivity change $[\Delta\sigma_{xx}(T)=\sigma_{xx}(T)-\sigma_{xx}(0)]$ as a function of temperature of various samples. We observe that the temperature dependence of $\Delta\sigma_{xx}(T)$ for all of our samples is accurately logarithmic, which further confirms the fact that EEI and WL effects are responsible for the anomalous resistivity variation at low temperature. The value of γ obtained from the above fitting is plotted with the function of carrier concentration in inset of Fig. 2. It is observed that the slope increases with the increase in the carrier concentration.

The magnetoconductivity ($B\neq 0$ perpendicular to samples surface) of all the investigated samples is positive and its magnitude decreases with an increase in temperature. This results from the temperature dependence of the inelastic scattering time, $\tau_\varphi \propto T^{-p}$. It was established that both WL and interaction effects contribute to the magnetic field dependent conductivity at low temperature. According to the theoretical model for highly mobile 2DEG systems, the magnetic field dependence of the localization correction to the conductivity is described by the following expression:[9,15]

$$\Delta\sigma_{xx}(B)=(e^2/4\pi^2\hbar)[F_t(b_\varphi,\ b_{so})-F_s(b_\varphi)]. \quad (4)$$

The first term is the interference contribution due to triplet state and the second term due to the singlet state. $b_\varphi=B_\varphi/B$ and $b_{so}=B_{so}/B$, where B_φ and B_{so} are the dephasing and spin-orbit scattering fields, respectively. $F_t(b_\varphi,\ b_{so})$ is given in the works of Minkov *et al.*[15] and Iordanskii *et al.*,[9] whereas $F_s(b_\varphi)=\psi(1/2+b_\varphi)-\ln(b_\varphi)$. ψ is the digamma function. The above expression for magnetoconductivity is valid for the diffusion approximation ($B\ll B_{tr}$), where $B_{tr}=\hbar/4eD\tau$ is the transport field and D is the diffusion coefficient.

The theory of the interaction is constructed for the case of electron scattering on a point (short range) potential[23] or for the case of Coulomb interaction (long range)[24] with a scatterer. For the case of point potential, the correction due to Fock exchange contribution is negative and it would make a positive magnetoconductance (MC), whereas, the Hartree contribution has the same functional form of Fock contribution but magnitude is twice and sign is opposite. For the case of Coulomb interaction, the Fock contribution leads to positive MC and the Hartree contribution produce the negative MC for $k\ll k_F$ (k and k_F are the inverse screening length and Fermi wave vector, respectively, and our samples satisfy this condition). Therefore, from the theory of interaction it is shown that the sign and magnitude of the MC changes due to the competition of the two (Fock and Hartree) types of contributions. We have calculated the contribution to the MC due to all types of interaction effects, as discussed above, at low magnetic field ($B<5$ mT) and low temperatures ($T<5$ K) using the theory mentioned in Refs. 23 and 24. We concluded that the calculated MC is about 10^4 times smaller than the experimental data. So, the contribution of the interaction effect at low fields to the MC data is negligible when compared with that of the WL contribution. Therefore, the experimental data can be analyzed only by using the WL theory.

Figure 3 shows the variation in the MC data plotted against the magnetic field for the sample with of 1.75 ML (i.e., the one with a nominal 1.75 ML of InAs, grown over GaAs). In order to obtain information on the magnitude of the dephasing scattering, the experimental curves were analyzed using the theory of WL. In the fitting procedure, the spin-orbit scattering is neglected due to the following reasons: first, measured magnetoconductivity curves do not show any antilocalization peak at low magnetic field. The presence of this peak is an indication of strong spin-orbit interaction. Second, the measured low field magnetoconductivity is positive throughout the investigated temperature range for all samples, which suggest the weak spin-orbit scattering ($B_{so}\ll B_\varphi$). Finally, whenever using B_φ and B_{so} as fitting parameters, the best fitted values of B_{so} are two to three orders smaller than B_φ. Therefore, B_φ is the only parameter determined from the fits on the plots of MC and the formulae predicted by the WL theories.

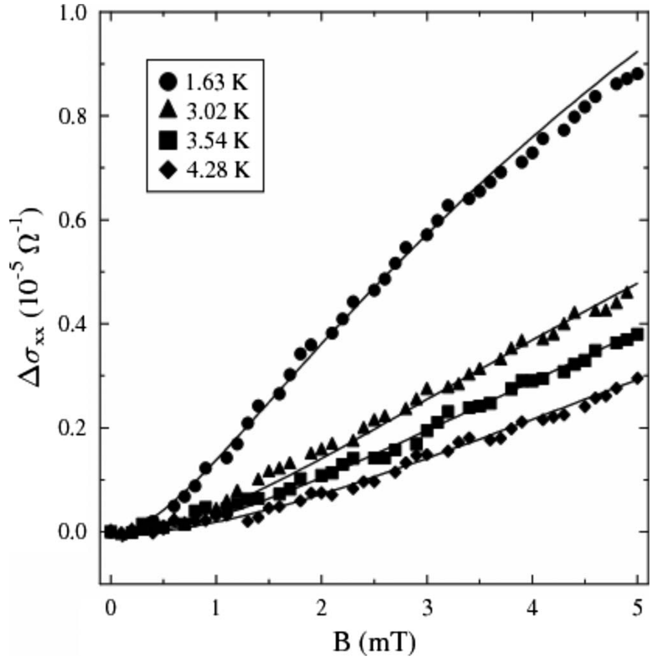

FIG. 3. Low field magnetoconductivity data of the sample 1.75 ML as a function of applied perpendicular magnetic field at different fixed temperatures. Points are measured data and solid lines are theoretical fits to Eq. (4). The carrier concentration and mobility are 1.97×10^{12} cm^{-2} and 0.55 m^2/Vs, respectively.

In Fig. 3, the different points represent the experimental data for different temperatures and the continuous lines are the theoretical best fitted values obtained using Eq. (4). As expected, the two-dimensional WL theoretical predictions can well reproduce the measured MC for both types of samples: with and without QDs. The dephasing scattering time τ_φ has been calculated by the relation $\tau_\varphi=\hbar/4eDB_\varphi$ and the variation in the scattering rates (τ_φ^{-1}) with temperature is shown in Fig. 4 for the sample with 1.75 ML. It is observed that the dephasing scattering rate depends strongly on the temperature.

In all probabilities, τ_φ assumes the role of the determining factor to control the magnitude and temperature dependence of the WL effect. In the absence of magnetic impurities, the phase relaxation originates from inelastic scattering,

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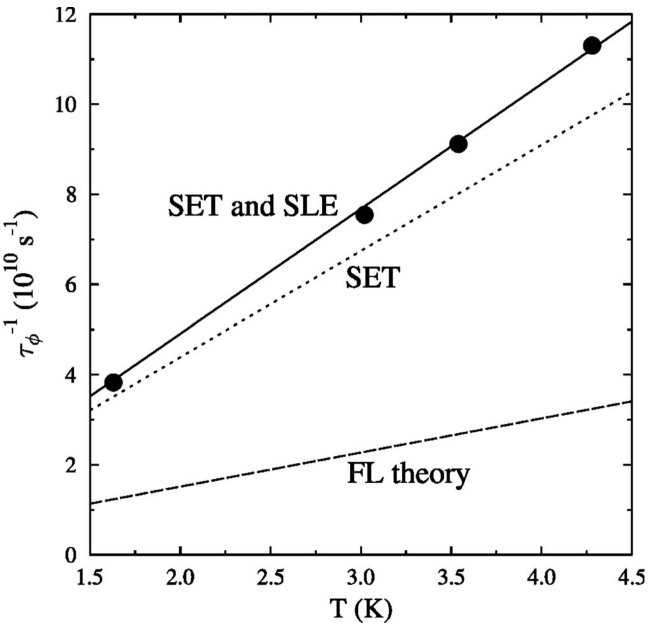

FIG. 4. Temperature dependence of the dephasing scattering rates. The solid line, dotted Line and dashed line represent theoretical values from Eq. (5)+Eq. (7), Eq. (5), and Fermi-liquid model respectively.

arising from the contribution of electron-phonon $(1/\tau_{e\text{-ph}})$ and electron-electron $(1/\tau_{ee})$ scatterings. On the basis of the theory of electron-phonon interaction,[25,26] we have calculated the value of $\tau_{e\text{-ph}}^{-1}$ by using the parameters of GaAs system. We find that, at the highest temperature of measurement, the magnitude of $\tau_{e\text{-ph}}^{-1}$ computed from theory is nearly two order smaller than the measured dephasing scattering rate for all the samples $[\tau_{e\text{-ph}}^{-1}(\text{theory})=3.378\times10^{8}\ \text{s}^{-1}$ and $\tau_{\varphi}^{-1}(\text{expt.})=1.123\times10^{11}\ \text{s}^{-1}$ at $T=4.28$ K of sample 1.75 ML]. The contribution of $\tau_{e\text{-ph}}^{-1}$ to the dephasing scattering rate is even less in the lower measurement temperatures, which almost rules out any probability for appreciable contribution from electron-phonon scattering to τ_φ. Therefore, the electron-electron scattering dominates the dephasing scattering in these systems at low temperatures.

The standard result for the electron-electron scattering rate in 2DEG (Ref. 27 and 28) at high temperature in clean systems $(k_BT\tau/\hbar\gg1)$ is proportional to T^2 and, at low temperature, where small energy transfer scattering processes dominate $(k_BT\tau/\hbar\ll1)$, it is proportional to T. But in all these calculations only the contribution of the singlet channel interaction is considered. However, Narozhny *et al.*[29] have calculated the dephasing scattering rate including the triplet channel interaction in both diffusive and ballistic regimes. According to their theory the temperature dependence of τ_{ee}^{-1} in the small energy transfer (SET) scattering processes $(k_BT\tau/\hbar\ll1)$ is given by the following expression:

$$\begin{aligned}\tau_{ee}^{-1}(T)=&[1+3(F_o^\sigma)^2/\{(1+F_o^\sigma)(2+F_o^\sigma)\}]\\&\times[k_BT/(g\hbar)]\ln[g(1+F_o^\sigma)]\\&+(\pi/4)[1+3(F_o^\sigma)^2/(1+F_o^\sigma)^2]\\&\times[(k_BT)^2/(\hbar\ E_F)]\ln(E_F\tau/\hbar),\end{aligned}\tag{5}$$

where $g=2\pi\hbar/(e^2R_\square)$ is the dimensionless conductance, $R_\square$ is the sheet resistance, E_F is the Fermi energy, and F_o^σ is the Fermi-liquid interaction constant in the triplet channel, which reflects the intensity of the spin exchange interaction. It is given by the relationship

$$\begin{aligned}F_o^\sigma=&-(1/2\pi)(r_s/\sqrt{(2-r_s^2)})\\&\times\ln[(\sqrt{2}+\sqrt{(2-r_s^2)})/(\sqrt{2}-\sqrt{(2-r_s^2)})],\quad\text{for}\ r_s^2<2,\end{aligned}\tag{6}$$

where r_s is the ratio of the Coulomb interaction energy to the kinetic energy, which can be obtained by the formula $r_s=\sqrt{2}e^2/(\varepsilon_s\hbar v_F)$. ε_s is the low frequency dielectric constant and v_F is the Fermi velocity. The theoretical value of F_o^σ have been calculated by using $\varepsilon_s=12.9$ for GaAs. For the sample 1.75 ML, it turned out that $F_o^\sigma=-0.20$. In order to compare the experimental result with theory, we have calculated the values of $\tau_{ee}^{-1}(T)$ from Eq. (5) and the Fermi-liquid model[22,27] by using $F_o^\sigma=-0.20$, $E_F=70.5$ meV, $\tau=0.212$ ps, and $\sigma_o=2.252\ \text{m}\Omega^{-1}$ and plotted in Fig. 4 as dotted and short dashed lines, respectively. It is observed from the figure that, although the temperature dependence of the experimentally measured dephasing rate is similar to the above theoretical predictions (linear in T), the magnitude did not match. This discrepancy probably arises due to another type of scattering like the scattering between 2D conduction electron-localized electron (trapped in QDs) (SLE), which is responsible for the samples containing quantum dots. According to this theory, the inelastic scattering rate is given by[30,31]

$$\tau_l^{-1}(T)=[(k_BT)^2/(\hbar E_{\text{el}})]|\ln(k_BT/\Delta\ |^3(N_{0\text{D}}/N_{2\text{D}}),\tag{7}$$

where E_{el} is an electronic energy (on the order of an electron volt), Δ is a characteristic value of the tunneling energy between localized states (on the order of a fraction of an electron volt), and $N_{0\text{D}}$ and $N_{2\text{D}}$ are the density of localized states and 2D conduction electrons respectively.

Figure 4 is a plot of the experimental $\tau_\varphi^{-1}(T)$ as a function of temperature for the representative sample with 1.75 ML of InAs. The symbols are the experimental data, while the solid curve is the theoretical values of $\tau_{ee}^{-1}(T)+\tau_l^{-1}(T)$, calculated from joint contribution of Eqs. (5) and (7) with best fitted parameters $E_{\text{el}}=80$ meV and $\Delta=45$ meV, and taking $F_o^\sigma=-0.20$, $E_F=70.5$ meV, $\tau=0.212$ ps, $N_{0\text{D}}=1.026\times10^{15}\ \text{m}^{-2}$ (density of localized electrons in the QDs), and $N_{2\text{D}}=1.97\times10^{16}\ \text{m}^{-2}$. It is evident from Fig. 4 that Eq. (5)+Eq. (7) can well describe our experimental τ_φ^{-1}.

So, one may conclude that the dephasing process occurs by means of joint contributions of the SET and SLE mechanisms in QDs samples. Figure 5 shows the linear dependence of $1/\tau_\varphi$ on the temperature, evidence that the second term on Eq. (5) is much smaller than the first one. Moreover, as the power of the $\ln(k_BT/\Delta)$ is not too different from Δ/k_BT behavior, the Eq. (7) shows also a linear dependence on T. Therefore, we can write $1/\tau_\varphi=A_{ee}T$.

Figure 6 shows the variation in the transport mobility (μ) and the angular coefficient (A_{ee}) as a function of the InAs layer width (d_{InAs}). Initially, the value of μ decreases and then suddenly increases at around $d_{\text{InAs}}=1.5$ ML and again decreases for further increase in d_{InAs}. This behavior of μ can be explained as follows. Initial growth of InAs layer

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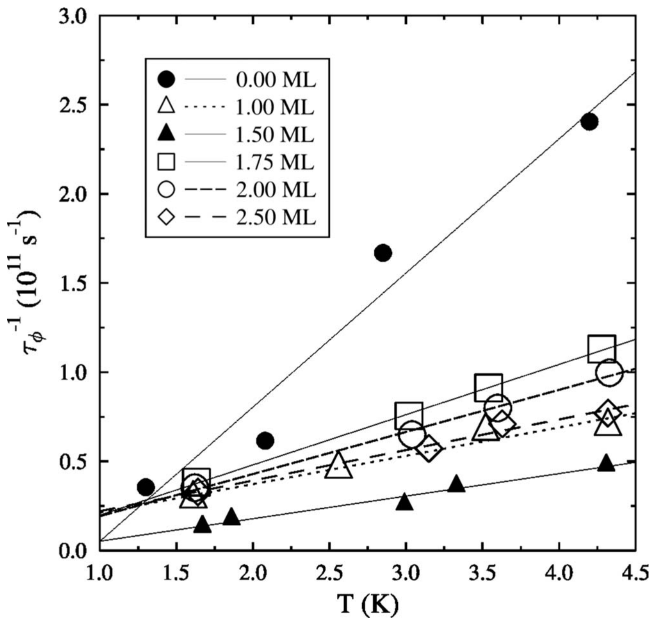

FIG. 5. Linear temperature variation in dephasing scattering rate for different samples.

on a GaAs surface leads to an intrinsic strain field due to the lattice mismatch up to a certain critical thickness $d_{\mathrm{InAs}}=1.5$ ML, where the QDs start to form. This increase in strain field reduces the mobility. As a mechanism of strain relieve, the quantum dots form spontaneously and mobility increases suddenly. However on further increase in the InAs layer ($d_{\mathrm{InAs}}>1.5$ ML), μ decreases due to the additional strain inside the QDs. The detail of this has been explained in Pagnossin *et al.*[32] The variation in A_{ee} with d_{InAs} also follows the similar type of behavior as observed in μ versus d_{InAs} variation.

To have a clear concept of this, we plotted the variation in A_{ee} with τ ($=m^*\mu/e$, m^* is the effective mass of electron) for the samples with and without QDs in the inset of Fig. 6. Although A_{ee} increases with the increase in τ in both cases, the slope of variation is different: in samples with QDs, additional scattering between the 2D conduction electrons and localized electrons enhances A_{ee} (i.e., τ_φ^{-1}) as the density of localized electrons increases, which results the decrease in the slope.

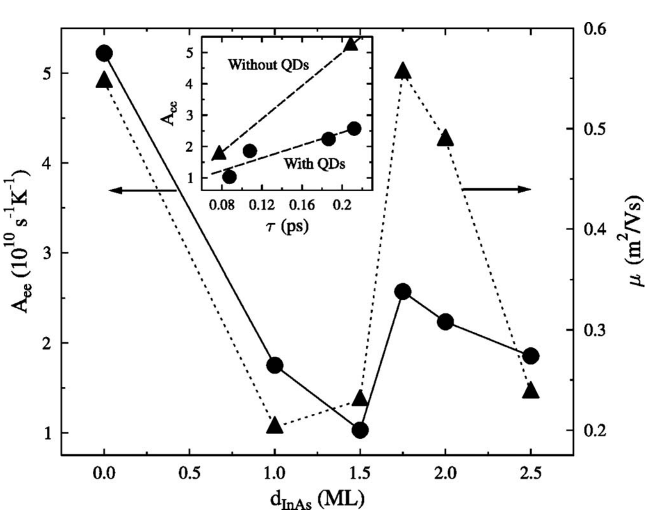

FIG. 6. Variation in temperature coefficient of the dephasing scattering rate and the transport mobility μ with monolayer of InAs. Inset shows the variation in A_{ee} with τ.

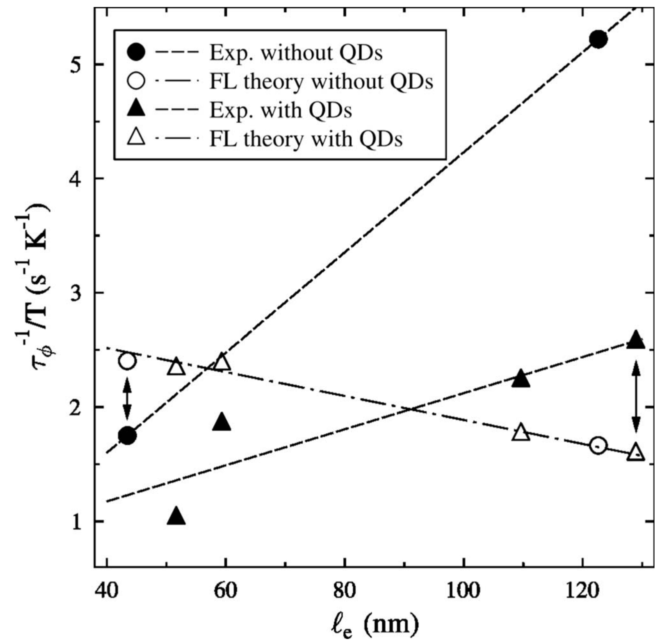

FIG. 7. Variation in τ_φ^{-1}/T with elastic mean free path (l_e) of different samples. Line-dot is the calculated values from the theoretical expression of Fermi-liquid model.

Figure 7 shows the relationship of τ_φ^{-1}/T with the electron mean free path (l_e) for all our samples. In any case (with and without quantum dots), $\tau_\varphi^{-1}\propto Tl_e$ (dashed line), whereas the Fermi-liquid theory (line-dot) predicts $\tau_\varphi^{-1}\propto T/l_e$; a clear mismatch (though actually, this result cannot be explained in terms of any existing theory of electron-electron interaction for impure materials[22,27,29,33]). From the experimental data it is possible to infer, empirically, that the strain accumulated during the epitaxial growth "freezes" the conducting electrons, as long as the dephasing process is related to the time randomness of the scatterers (electrons, as discussed until now). This process, which we cannot model by now, may overrule the standard phase breaking mechanism considered by the Fermi-liquid theory (electron-electron interaction) and account for this anomalous behavior of τ_φ^{-1}. Anyway, more studies are necessary to formulate the true mechanism and this experimental result may add impetus to the theoretical community to think about this issue

In view of the effort exerted to understand the mechanism of dephasing scattering in the diffusive limit, it is to be examined whether the experimental data in the present investigation satisfy the diffusive criterion $k_BT\tau/\hbar\ll 1$. Substituting the values of τ for different samples, the value of $k_BT\tau/\hbar=(0.01-0.028)T$, where T is in Kelvin. Therefore, it is worth mentioning here that the dephasing processes in the present study meet the diffusive criterion of $k_BT\tau/\hbar\ll 1$, even at the highest temperature of measurement. The transport field $B_{\mathrm{tr}}=\hbar/4eD\tau$ was also estimated for the samples and found that B_{tr} varies from 20 to 174 mT. Since analysis of MC was done at low magnetic field ($B=5$ mT), the dif-

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fusion approximation ($B < B_{tr}$) is satisfied and it can be concluded that WL theory is well suited to explain the trends shown by the magnetoconductivity.

IV. CONCLUSION

We have measured the electrical conductivity of several samples in the absence and in the presence of the perpendicular magnetic fields. For $B=0$, the conductivity of all samples increases with increasing temperature and the conductivity rise indeed varies linearly with $\ln(T)$, firmly supporting the joint contribution of WL and EEI: for $B \neq 0$, it was observed that the electron-electron interaction contribution to the MC is very small comparing to the weak-localization one. The observed linear temperature dependence of the dephasing scattering rate τ_φ^{-1} can be described by electron-electron interaction due to the small energy transfer processes along with the interaction between 2DES and localized electrons in QD samples. The temperature coefficient of the dephasing scattering rate shows similar trend of variation with different slopes for the samples with and without QDs. Moreover, our results indicate linear mean free path dependence, i.e., $\tau_\varphi^{-1} \propto l_e$, which is against Fermi-liquid model and whose origin is still not clear. So our results, $\tau_\varphi^{-1} \propto T l_e$, should make us rethink what heretofore has been taken for granted concerning electron-electron scattering in two-dimensional GaAs/InGaAs heterostructures in presence of InAs quantum dots.

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