Dimensional crossover and weak localization in a 90 nm *n*-GaAs thin film

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We report on the magnetotransport in a 90 nm thick n-type GaAs epitaxial thin film in the weak localization (WL) regime. Low temperature ($T \leq 50$ K) magnetotransport data are fit with WL theory, from which the phase coherence time, $\tau_\phi \propto T^{-p}$ ($p = 1.22 \pm 0.01$), are extracted. We conclude that the dominant dephasing mechanism at these temperatures is electron-electron (e-e) scattering in the Nyquist limit. Evidence of a crossover from two-dimensional to three-dimensional behavior with respect to both coherent transport (WL) and e-e interactions is observed in the temperature dependence of the zero-field conductivity and τ_ϕ, respectively. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3176968]

Although nanoscale physics in the ballistic regime is an elegant and interesting topic, there are many applications requiring nanoscale devices that retain diffusive transport for application. Examples include devices based on the geometrical enhancement of classical properties such as extraordinary magnetoresistance[1] (EMR) and more recently extraordinary electroconductance[2] (EEC) for high resolution magnetic (B) and electric (E) field sensing, and the nonballistic spin transistor.[3] Diffusive transport requires that, these devices must have dimensions greater than the elastic mean free path $\lambda_p = \sqrt{D\tau_p}$, where D is the electron diffusion constant and τ_p is the elastic scattering time. Materials with high room temperature (RT) mobility (μ) such as InSb are an obvious choice for high B-field sensitivity (Hall $\propto \mu$, EMR $\propto \mu^2$),[4] but enter the ballistic regime at relatively large dimensions and require demanding fabrication strategies to regain diffusive transport at the nanoscale.[1] Alternatively, materials with lower μ, such as GaAs, offer the potential for high resolution sensing without the above mentioned difficulties and are also the material of choice for spintronics.[5,6] A thin conducting layer in close proximity to the target medium is advantageous for B-field sensing, e.g., quantum wells or thin epitaxial films. The latter offer advantages in terms of cost and processing complexity and are also applicable to the EEC effect. Accordingly, we report here and quantitatively account for the magnetotransport properties of a thin (90 nm) n-type GaAs film which exhibits the desirable characteristics noted above.

Electron transport in disordered systems has attracted much interest over the past 30 years.[7–9] It is an ideal tool for probing electron-electron (e-e) interactions[10] and weak localization (WL).[11] Nevertheless, few studies have been reported on three-dimensional (3D) semiconductor thin films. Savchenko *et al.*[12] reported on WL in a pre-illuminated GaAs film. Murzin *et al.*[13] addressed the quantum Hall effect in buried n-GaAs thin films with 3D character, which was described in terms of e-e interactions induced at high B >6 T, beyond the WL regime. The sample addressed here differs from those studied previously in that the conducting layer is located at the surface of the structure, preferable for sensing applications.

The strength of e-e interactions can be characterized by the ratio between the Coulomb and Fermi energies. In 3D this is given by $r_s = [(3/4)\pi n a_0^3]^{1/3}$,[14] where n is the 3D carrier density and a_0 is the effective Bohr radius. For $r_s < 1$ (weakly interacting) as is the case in our sample ($r_s \sim 0.8$, see below), the effects of e-e interactions (at low B) are expected to be small. Here, we focus on the analysis of WL in low fields which persists up to higher temperatures (≤ 50 K) and fields than that reported for two dimensional electron gases (2DEGs).[15] In two dimensions, WL yields a logarithmic T-dependent correction to the zero-field conductivity, $\sigma_{xx}(0,T)$, which exists as long as $\tau_\phi \gg \tau_p$, where $\tau_\phi \propto T^{-p}$ is the phase coherence time;[11] p depends on the nature of the scattering. The application of a B field normal to the sample suppresses the WL correction and produces a characteristic, negative magnetoresistance (MR). The observation and subsequent fitting of this feature to WL theory provides a method for determining τ_ϕ.

The effect of dimensionality on the electrical conduction in thin films of thickness, t, has been investigated.[16] For normal conduction, a system is 2D when $t < \lambda_p$. In the context of WL, the criterion for 2D is $t < \lambda_\phi$, where $\lambda_\phi = \sqrt{D\tau_\phi}$ is the Thouless length. Since λ_ϕ generally decreases as T increases, at low T, λ_ϕ can exceed λ_p by orders of magnitude and it is possible for a film which is intrinsically 3D, to be 2D with respect to WL. Furthermore, there is a 2D to 3D WL crossover above a characteristic temperature when $\lambda_\phi \approx t$ that has been reported in metallic systems,[16] but not in semiconductor films.

The sample addressed here was grown by molecular-beam epitaxy, lattice-matched onto a GaAs (001) substrate [see inset Fig. 1(a)]. The Si-doped ($N_d = 4 \times 10^{17}$ cm^{-3}) n-GaAs layer may be characterized by a wide and smooth potential well formed by the narrow region of ionized impurity charge. Magnetotransport measurements were performed between 2 and 290 K in perpendicular magnetic fields up to

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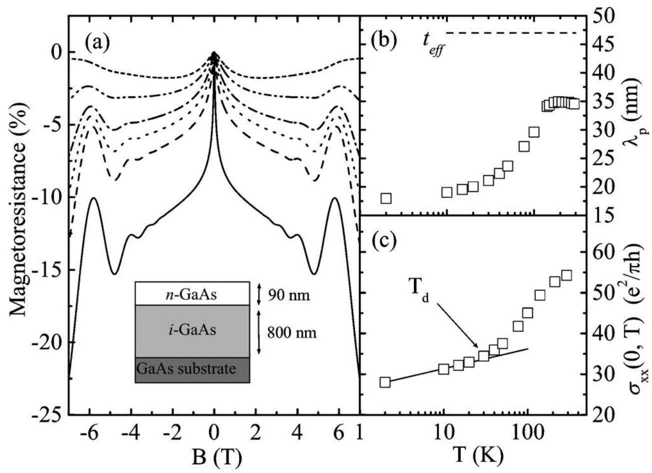

FIG. 1. (a) The MR at $T=2$, 10, 15, 20, 30, and 40 K (from bottom to top). Inset: A schematic of the layer structure. (b) Temperature dependence of the elastic mean free path. The solid line shows the effective layer thickness. (c) $\sigma_{xx}(0,T)$ exhibiting logarithmic behavior (solid line) below the crossover temperature T_d.

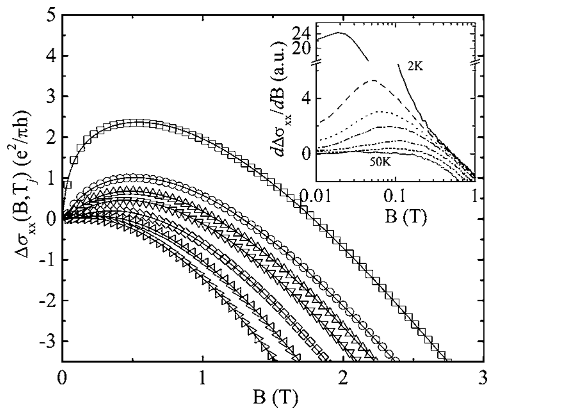

FIG. 2. The magnetoconductivity $\Delta\sigma_{xx}(B,T_j)$ for $T=2$ K (□), 10 K (○), 15 K (△), 20 K (▽), 30 K (◇), 40 K (◁), and 50 K (▷). Solid lines show the fits to Eq. (2). Inset: $d\Delta\sigma_{xx}/dB$ vs B showing the characteristic WL peak at low field.

7 T using a standard four-point ac lock-in technique.

Figure 1(a) shows the MR for various temperatures below 50 K. Two regimes can be distinguished. In high fields ($B>3$ T), weak Shubnikov–de Haas (SdH) oscillations are resolved, typical of that in bulk material. In low fields ($B<2$ T) a strong negative MR associated with the WL effect is seen. The carrier density, n_{SdH}, is directly determined from the periodicity of SdH oscillations to be 2.83×10^{17} cm^{-3} at 2 K. The ratio $n_{\mathrm{SdH}}/N_d=0.7<1$ is attributed to the loss of carriers to the surface. The carrier mobility is determined from the sheet resistance and sheet Hall coefficient[17] ($R_{\mathrm{HS}}=1/\mathrm{net}$) to be 1660 cm^2 V^{-1} s^{-1} (3225 cm^2 V^{-1} s^{-1}) at 2 K (290 K). These are an order of magnitude higher than reported in a previous study of WL on thin GaAs films[12] but consistent with those found in bulk material of comparable carrier density.[18] We note that unlike the case for bulk GaAs layers n and μ vary only by a factor of 1.05 and 2, respectively, over the entire temperature range. This property is obviously beneficial for a number of applications.

With no bounding heterointerfaces, the effective film thickness, t_{eff}, is expected to differ from the nominal thickness, $t=90$ nm.[13] A low temperature estimate of t_{eff} can be made using $t_{\mathrm{eff}}\approx 1/(R_{\mathrm{HS}}en_{\mathrm{SdH}})$, yielding $t_{\mathrm{eff}}\approx 47$ nm. This reduction is large compared to that for buried thin films (20%) (Ref. 13) and is enhanced due to the depletion region at the air/GaAs interface which introduces additional band bending and channel narrowing (assuming that the Fermi level is pinned around mid-gap due to surface states).[19] This effect is unique to thin semiconductor films. We note that in the regime where t_{eff} is comparable to the depletion width, the sensitivity of the film conductance to an applied E-field is maximal and thus optimal for EEC device applications.[2] Figure 1(b) shows the temperature dependence of the $\lambda_p \propto \mu n^{1/3}$. This essentially reflects the dependence of μ since n is relatively temperature independent. It can be seen that $t_{\mathrm{eff}}>\lambda_p$ is satisfied over the entire range and therefore the film is expected to have a 3D energy spectrum. Figure 1(c) shows $\sigma_{xx}(0,T)$. Below a certain temperature, T_d, the conductivity decreases logarithmically in agreement with WL theory.[11] Here T_d denotes a smooth crossover from 3D $\rightarrow$2D WL in analogy with previous results.[16]

The magnetoconductivity (MC) arising from 2D WL, $\Delta\sigma_{xx}^{\mathrm{WL}}(B,T)=\sigma_{xx}^{\mathrm{WL}}(B,T)-\sigma_{xx}^{\mathrm{WL}}(0,T)$, is[7]

$$\Delta\sigma_{xx}^{WL}(B,T) = \alpha\frac{e^2}{\pi h}\left[\psi\left(\frac{1}{2}+\frac{B_p}{B}\right)-\psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right)\right]. \tag{1}$$

Here ψ is the digamma function, α is a constant of order 1, while $B_p=\hbar/4eD\tau_p$ and $B_\phi=\hbar/4eD\tau_\phi$ are the characteristic fields. Equation (1) is valid for $B<2B_p$ (diffusive limit) which in our sample is large, e.g., $2B_p\sim1.4$ T at 2 K. To minimize the number of fitting parameters we ignore spin-orbit and Zeeman contributions both of which are small.[20] We include the Drude MC so that

$$\Delta\sigma_{xx}^{T}(B,T) = ne\mu\left[\frac{1}{(1+\mu^2B^2)}-1\right]+\Delta\sigma_{xx}^{WL}. \tag{2}$$

The B-dependent conductivity at fixed temperature, T_j, is obtained from $\sigma_{xx}(B,T_j)=\rho_{xx}(B,T_j)/[\rho_{xx}^2(B,T_j)+\rho_{xy}^2(B,T_j)]$. (Analyzing the conductivity has the benefit that any interaction corrections in $\rho_{\mathrm{xx}}(B)$ are insensitive to magnetic field in $\sigma_{\mathrm{xx}}(B)$, thus simplifying the analysis.) The resulting least-squares fits of Eq. (2) to the MC are shown in Fig. 2. The inclusion of the Drude component enables a fit up to significantly larger magnetic fields ($\leq 2B_p$) than is possible using Eq. (1) alone. Furthermore, good agreement extends beyond the diffusive limit. The only fitting parameters are τ_ϕ and α; we take $\tau_p=\mu m^*/e$ with $m^*=0.063m_0$.[19] The inset of Fig. 2 shows $d\Delta\sigma_{xx}(B,T_j)/dB$. A distinctive T-dependent peak is present at low field. We identify this feature as a direct signature of WL.

The temperature dependences of τ_ϕ and α are shown in Fig. 3. A least-squares fit to $\tau_\varphi=\tau_p(T_0/T)^p$ yields $p=1.22\pm0.01$ and $T_0=265\pm8$ K. In metallic and semiconductor systems at low temperatures, inelastic e-e scattering is the dominant source of dephasing.[9] Nyquist dephasing in 2D (Ref. 21) yields $\tau_{N(2\mathrm{D})}\propto T^{-1}$ which is in reasonable agreement with the magnitude of our data but not with the temperature dependence. This 2D model is valid for $T<D\hbar/(2\pi kt^2)$, beyond which the film is considered 3D with respect to e-e interactions and $\tau_{N(3\mathrm{D})}\propto T^{-1.5}$.[21] Since we expect the 2D$\rightarrow$3D transition to be smooth, we consider the Matthiesson result $\tau_{\langle N\rangle}^{-1}\approx\tau_{N(2\mathrm{D})}^{-1}+\tau_{N(3\mathrm{D})}^{-1}$, which gives excel-

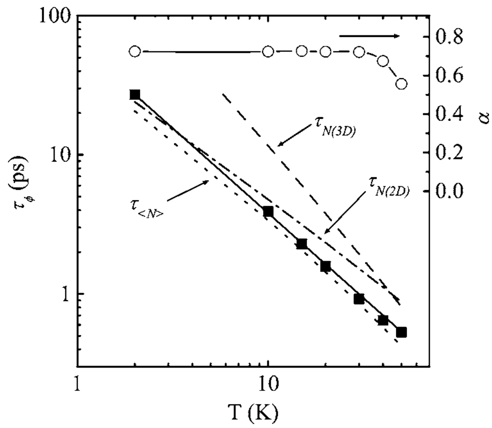

FIG. 3. The temperature dependence of τ_ϕ obtained from the fitting of Eq. (2). The solid line is a least-squares power law fit. The dot-dashed and dashed lines are the theoretical predictions based on Nyquist dephasing in 2D and 3D, respectively (Ref. 21), and the dotted line is $\tau_{\langle N\rangle}^{-1} \approx \tau_{N(2\mathrm{D})}^{-1} + \tau_{N(3\mathrm{D})}^{-1}$.

lent agreement with our results. (Both theoretical dependences are scaled by pre-factors containing no free parameters). This provides compelling evidence for a crossover from 2D (at low T) to 3D (high T) with respect to e-e interactions.

Inelastic scattering from electron-phonon interactions, τ_{ep}, which are expected to become important at high T and be the sole contribution to τ_ϕ in 3D metallic systems ($\tau_{\mathrm{ep}} \propto T^{-2}$ and $\propto T^{-3}$ for transverse and longitudinal phonons, respectively)[9] do not account for either the magnitude or temperature dependence of our data. Our extracted values for τ_ϕ and p based on Eq. (2) are in good agreement with values for GaAs 2DEGs ($p \approx 1$) (Ref. 8) and a GaAs thin film ($p=0.82$).[12] Because the phase coherence length $\lambda_\phi < t$ for $T \geq 40$ K, analyzing the 40 and 50 K data with Eq. (1) becomes increasingly invalid. This is evidenced by a reduction in α (see Fig. 3). However, the good agreement found indicates that the film retains some 2D WL behavior even at elevated temperature. These observations are consistent with T_d estimated from $\sigma_{xx}(0,T)$ [see Fig. 1(c)] and strengthen the conjecture of dimensional crossover in the WL regime.

The lack of quantization and of either spin-orbit or Zeeman contributions, simplifies the analysis of the MC compared to 2DEGs, and makes thin films ideal for the study of WL. In addition to the number of interesting low temperature phenomena reported here, we conclude that these thin films are attractive for RT EMR and EEC applications that require diffusive transport devices that are of the order 100 nm or less, with relatively T-insensitive bulk properties. In addition, the sensitivity of the film to the surface potential makes the use of a gate viable, thus enhancing the potential modulation of the conductance and spin relaxation for EEC and spintronic applications, respectively.[6]

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