Lifetime of two-dimensional electrons measured by tunneling spectroscopy

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For electrons tunneling between parallel two-dimensional electron systems, conservation of in-plane momentum produces sharply resonant current-voltage characteristics and provides a uniquely sensitive probe of the underlying electronic spectral functions. We report here the application of this technique to accurate measurements of the temperature dependence of the electron-electron scattering rate in clean two-dimensional systems. Our results are in qualitative agreement with existing calculations.

Several scattering mechanisms contribute to limiting the quantum lifetime of electrons in semiconductors. At low temperature, the lifetime of electrons close to the Fermi surface is dominated by elastic scattering off of the static disorder potential in the material. At higher temperatures, inelastic processes like electron-phonon and electron-electron scattering take over. Electrical transport measurements are often adequate for the study of the elastic scattering and the electron-phonon processes. The electron-electron scattering time τ_{ee}, however, is much harder to extract from transport experiments since such processes conserve the total momentum of the electron system. More sophisticated techniques involving quantum interference have been used[1] to extract a "dephasing" time τ_ϕ which is closely related to τ_{ee}. Though roughly comparable in magnitude, these two times are not precisely equivalent.[2] In this paper we report a *direct* determination of the lifetime of two-dimensional (2D) electrons based upon the method of tunneling spectroscopy.[3] While this[4] and other[5] methods have been applied to determine *hot* electron-LO phonon scattering times, here we are concerned with the much weaker scattering processes which limit the lifetime of thermal electrons near the Fermi level. Crucial to the success of our method is the conservation of in-plane momentum. This constraint greatly restricts the phase space available for tunneling between parallel 2D systems and allows unique access to the underlying electronic spectral function $A(E,k)$. This function, which gives the probability that an electron with wave vector k has energy E, possesses a strong peak near the single-particle energy $\hbar^2k^2/2m$. The width of this peak, the quantity measured in these experiments, reflects the finite lifetime of the momentum eigenstates.

In these experiments we measure the tunnel current flowing perpendicularly between two parallel 2D electron systems (2DES) separated by a barrier. In the ideal case (i.e., no disorder, electron-electron interactions, etc.), the conservation of in-plane momentum implies that an electron can tunnel only if the quantized energy levels in the two wells line up precisely.[6] This implies that the current-voltage characteristics of an ideal 2D-2D tunnel junction are singular; the tunneling conductance is zero everywhere except at those discrete voltages which produce alignment of the proper energy levels. This unusual situation contrasts sharply with 2D-3D and 3D-3D junctions where tunneling proceeds over an energy range comparable to the Fermi energy E_F. In real 2D-2D junctions, the tunnel resonances will have a finite width, set not by E_F, but only by the degree to which the conditions of the ideal model break down. Loss of momentum conservation due to imperfections in the tunnel barrier is one source of broadening. But even with a perfect barrier, the finite lifetime of individual electronic (momentum) states in either 2DES will broaden the tunnel resonance.[7] As we shall see, the contribution of electron-electron scattering to this latter effect dominates the temperature dependence of the observed tunneling linewidth.

The double quantum well (DQW) heterostructures used in this experiment consist of two 200-Å-wide GaAs quantum wells separated by an undoped $Al_xGa_{1-x}As$ barrier. Samples with barrier widths ranging from 175 to 340 Å and Al mole fractions $0.1 < x < 0.33$ have been studied. Total densities ranged from 1 to 1.6×10^{11} cm^{-2} with low-temperature mobilities in excess of 10^6 cm^2 /V s. The densities in each quantum well could be further adjusted using gate electrodes deposited on the top and bottom of the sample. Ohmic contacts to the individual 2DES layers[8] were placed at the ends of narrow arms protruding from a 250-μm square central mesa. With these contacts we could directly measure the tunneling conductance dI/dV (using 17-Hz, 0.1-mV excitation) as a function of the dc interlayer voltage V.

Figure 1 shows typical dI/dV vs V tunnel resonances at four temperatures between $T = 0.7$ and 10 K from a sample with equal 2DES densities ($N_s = 1.6 \times 10^{11}$ cm^{-2}) in each quantum well. These resonances are centered at zero voltage since, with equal densities in the two wells, the alignment of the lowest subband energy levels required for tunneling occurs simultaneously with the alignment of the Fermi levels. Note that the observed widths of the tunnel resonances (~ 0.5 meV) are much less than the Fermi energies ($E_F \approx 5.7$ meV) of the 2DES's. This implies a high degree of momentum conservation in tunneling.[9] Figure 1 also reveals that as the temperature rises, the peak tunneling conductance falls while the width of the resonance increases. We shall argue that this behavior reflects the decreasing electronic lifetime, due to electron-electron scattering, in each quantum well.

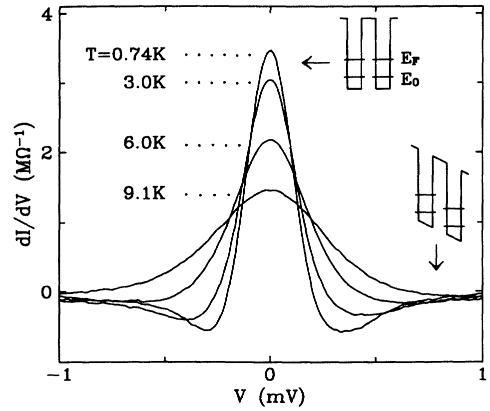

FIG. 1. Typical 2D-2D tunneling resonances observed at various temperatures in a sample with equal densities (N_s = 1.6 × 10^{11} cm^{-2}) in the two 2DES's. Insets show simplified band diagrams on and off resonance.

Instead of analyzing the measured dI/dV data directly, it is more convenient to study the ratio $I/V \equiv F(V)$. We construct this ratio after numerically integrating the measured dI/dV to obtain the tunnel current.[10] This ratio has two important attributes. First, as shown below, for momentum conserving tunneling $F(V)$ is just the convolution of the fundamental spectral functions $A(E,k)$ of the two 2D electron systems. Second, since $F(V)$ is the *ratio* of current to voltage, it gives a fair assessment of the tunneling current which is observed well away from the main resonance itself. (This nonresonant current is only weakly voltage dependent and thus hardly appears in dI/dV.) The dotted curves in the inset to Fig. 2 are the $F(V)$ functions derived from the raw tunneling data

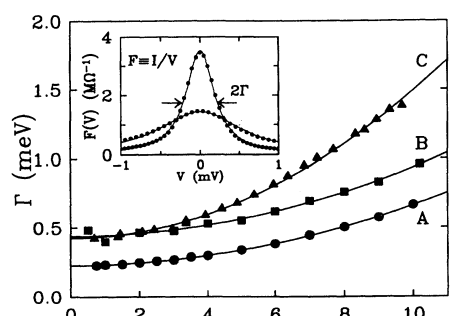

FIG. 2. Temperature dependence of the tunneling linewidth Γ for three samples. Samples A and B have comparable 2DES densities (N_s = 1.6 and 1.5 × 10^{11} cm^{-2}) but different amounts of static disorder [i.e., different $\Gamma(T=0)$]. Sample C has a lower density (0.8 × 10^{11} cm^{-2}). Inset: Dotted curves are the ratios $F(V) = I/V$ determined from the measured dI/dV traces at T = 0.74 and 9.1 K shown in Fig. 1. (The point density has been reduced for clarity.) The definition of the linewidth Γ is shown. The solid curves are Lorentzian fits to the $F(V)$ data.

shown in Fig. 1. As expected, $F(V)$ is strongly peaked around $V = 0$ and falls steadily toward zero off resonance. The solid curves in the inset are simple Lorentzian fits to the $F(V)$ data. Only the amplitude and width of the Lorentzian is adjusted; the fits contain *no* vertical offsets. It is thus clear that the tunneling in these samples is dominated by a single, highly momentum-conserving, resonant process and that the off-resonance tunnel currents are of secondary importance.

Figure 2 also shows the temperature development, for three samples, of the resonance width Γ. The numerical value of Γ is taken to be the half width at half maximum (HWHM) of the experimental $F(V)$ function. (In spite of the near-Lorentzian shape of the resonances, line-shape fitting is not employed.) Below about T = 2 K, Γ is temperature independent, indicating that inelastic processes have become negligible. In this regime the resonance width is sensitive to density inhomogeneities, momentum nonconservation due to barrier imperfections, and the finite lifetime of the electrons in each 2DES produced by scattering off of the static disorder potential (e.g., the Si donors). For sample A, the low-temperature width Γ_0 = 0.22 meV compares favorably with the quantum lifetime extracted from analysis of the measured Shubnikov–de Haas resistivity oscillations ($\hbar/\tau$ = 0.17 meV). This suggests that even at low temperatures the tunneling resonance width is dominated by the quantum lifetime of the 2D electrons and not by breakdown of momentum conservation. We do not emphasize this point, however, since it is the finite temperature linewidth which we are most interested in here. Figure 2 shows that as the temperature is increased Γ grows, essentially as T^2. This broadening is *not* simply due to thermal smearing of the Fermi distribution of the 2DES, since the constraint of momentum conservation is indifferent to the thermal population of the various momentum states. Rather, the increasing resonance width signals the onset of inelastic processes which shorten the electronic lifetime. Of the three samples displayed in Fig. 2, two (A and B) have different levels of disorder, as evidenced by their different low-temperature linewidths Γ_0, but equal 2DES densities. Sample C, however, has the same Γ_0 as sample B but lower density. From this we conclude that the temperature-dependent part of the linewidth depends upon density but not disorder. This suggests an inelastic process, like electron-electron (e-e) or electron-acoustic phonon (e-ph) scattering. The e-ph scattering rate can be independently determined from the temperature dependence of the 2DES mobility μ. Above a few Kelvin, e-ph scattering is not limited to small angles, and we can directly compare the mobility lifetime broadening $\hbar/\tau_\mu$ to the measured tunnel resonance linewidth.[11] This comparison shows that $\hbar/\tau_{eph}$ is roughly 50 times smaller than Γ at T = 10 K. Thus e-ph scattering within each 2DES is a minor contributor to the net electronic lifetime in this experiment. Phonon-assisted tunneling processes can also be ruled out since the opening up of such a new tunneling channel would presumably increase the peak tunnel conductance, whereas it is observed in fact to *decrease*. We believe instead that e-e scattering is responsible for the observed temperature dependence of Γ.

To quantitatively analyze our data we begin with the generalized Golden Rule expression[12] for the tunnel current flowing between the left (L) and right (R) quantum wells:

$$I = \alpha \sum_{k,k'} |T_{k,k'}|^2 \int_{-\infty}^{\infty} dE \int_{-\infty}^{\infty} dE' A_L(E,k) A_R(E',k') \times [f(E) - f(E')]\, \delta(E - E' - eV), \quad (1)$$

where α is a constant, $T_{k,k'}$ the tunneling matrix element, and $f(E)$ is the Fermi function. With E measured from the Fermi level E_F the spectral function $A(E,k)$ is a function of $x = E + E_F - \hbar^2 k^2/2m$, possessing a sharp peak near[13] $x = 0$. Near this "quasiparticle" peak $A(E,k)$ is usually taken to be a Lorentzian: $A(x) = (\gamma/2\pi)/(x^2 + \gamma^2/4)$, with γ representing the lifetime broadening $\gamma = \hbar/\tau$ of the quasiparticles. [Note that the HWHM of $A(E,k)$ is $\gamma/2$.] Imposing momentum conservation (i.e., $|T_{k,k'}|^2 = |t|^2 \delta_{k,k'}$) and assuming, for simplicity, that $k_B T$ and γ are much less than E_F (as in our experiment), reduces Eq. (1) to

$$\frac{I}{V} = \beta |t|^2 \int_{-\infty}^{\infty} dx\, A_L(x) A_R(x + E_{F,R} - E_{F,L} - eV), \quad (2)$$

with β a constant. Thus, the ratio $I/V \equiv F(V)$ is just the convolution of the spectral functions[14] and exhibits a maximum when $eV = E_{F,R} - E_{F,L}$, i.e., when the energy levels in the quantum wells are aligned. If the two layers have the same density, this occurs at $V = 0$. Note that the Fermi functions do not enter in $F(V)$. As long as $k_B T$ and $\gamma_{L,R}$ remain much less E_F, this consequence of momentum conservation implies that the observed temperature dependence of the tunnel resonance comes only from the spectral widths $\gamma_{L,R}$. Note also that for Lorentzian spectral functions, $F(V)$ is also Lorentzian, exhibiting a HWHM of $\Gamma = (\gamma_L + \gamma_R)/2$. Thus, Γ, our experimentally measured quantity, is just the average lifetime broadening $\hbar/\tau$ of an electron in the double-layer system.[15]

Figure 3 summarizes our results for the temperature dependence of Γ extracted from tunnel resonances observed with equal 2D densities in the quantum wells. In all cases we have found Γ to be well approximated by $\Gamma(T) = \Gamma_0 + \alpha T^2$. The inset to Fig. 3 shows that the coefficient α is inversely proportional to the 2D density N_s. Data from all samples and densities[16] are displayed together in the main panel of Fig. 3. The data collapse reasonably well onto a single curve if, for each density, we plot $(\Gamma - \Gamma_0)/E_F$ vs T/T_F, where T_F is the Fermi temperature. This behavior is consistent with electron-electron scattering in a clean 2DES.

There is disagreement among the various theoretical calculations of the thermal e-e scattering rate. Hodges, Smith, and Wilkins[17] first showed that for a 2D electron at the Fermi level $\hbar/\tau_{ee} \propto T^2 \ln(T_F/T)$ at low temperature. Subsequently, Giuliani and Quinn[18] (GQ) found

$$\frac{\hbar}{\tau_{ee}} = \frac{E_F}{2\pi} \left(\frac{T}{T_F}\right)^2 \left[\ln\left(\frac{T_F}{T}\right) + 1 + \ln\left(\frac{2q_{TF}}{k_F}\right)\right] \quad (3)$$

where q_{TF} is the 2D Thomas-Fermi screening wave vector

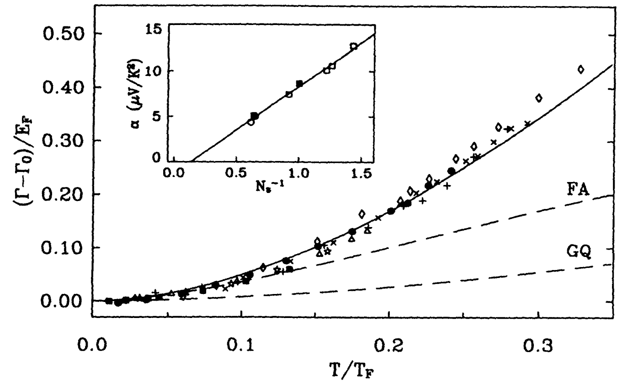

FIG. 3. Tunnel resonance width vs temperature for all samples (having eight different densities). On dividing T by T_F and the resonance width (minus the zero-temperature limit Γ_0) by E_F all the data collapse onto a single curve. The dashed lines are the calculations of GQ (Ref. 18) and FA (Ref. 20). The solid line is 6.3× GQ. Inset: Coefficient of T^2 term in Γ vs inverse density N_s^{-1} (in units of 10^{-11} cm^2).

(2×10^6 cm^{-1} in GaAs) and k_F is the Fermi wave vector. This expression[19] is the dashed line labeled GQ in Fig. 3. Fukuyama and Abrahams[20] (FA), however, found a $T^2 \ln(T_F/T)$ term π^2 larger than GQ; this result is also shown in the figure. Additionally, Fasol[21] and Yacoby *et al.*[1] both report numerical calculations of $\hbar/\tau_{ee}$ which exceed Eq. (3) by a factor of two.

The measured scattering rate in this experiment is roughly 6 times larger than the GQ result. We note that Yacoby *et al.*[1] and Berk *et al.*,[22] using different methods, have also reported e-e scattering rates significantly larger than the GQ prediction. Since our data possess the temperature and density dependences expected for e-e scattering in clean 2D systems, and the magnitude is comparable to the various theoretical estimates, we believe that the operative broadening mechanism has been identified. Nevertheless, we comment on three potential sources of enhanced scattering. First, in a *diffusive* 2D system, the e-e scattering rate is enhanced,[23] with τ_{ee}^{-1} varying linearly with temperature. This effect, however, is unlikely to be important here. Aside from possessing a different temperature dependence, the observed inelastic scattering rate $(\Gamma - \Gamma_0)/\hbar$ dominates the static disorder rate $\Gamma_0/\hbar$ at high temperature. This implies that the electrons move ballistically between inelastic events. Another possible contribution to Γ arises from *interlayer* Coulomb interactions. Recent studies[24] of the interlayer e-e scattering rate in samples similar to ours show that this process can be safely ignored, even after allowing for the contribution of acoustic interlayer plasmons.[25] In any event, these interlayer processes cannot be very important, since we find no dependence of Γ on the tunnel barrier thickness (between 175 and 340 Å). Finally, we note that Eq. (3) is applicable only at very low temperatures for electrons exactly at the Fermi level and assumes that all many-body effects beyond random-phase approximation are negligible. Each of these assumptions is violated to some extent by the conditions of our experiment.

In summary, we have applied the technique of 2D-2D tunneling spectroscopy to determining the spectral properties of electrons in semiconductor quantum wells. The density and temperature dependences of the thermal electron-electron scattering rate have been measured. We believe that this method will find numerous further applications.

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[10] In those instances where the tunnel current I was directly measured, it agreed excellently with the numerically integrated dI/dV.

[11] Above about $T = 2$ K, the thermal acoustic phonon wave vector exceeds $2k_F$ and large angle scattering dominates $\tau_{\rm eph}$. For $T \geq 4$ K the mobility becomes significantly temperature dependent owing to these e-ph processes.

[12] See E.L. Wolf, *Principles of Electron Tunneling Spectroscopy* (Oxford University Press, New York, 1985).

[13] R. Jalabert and S. Das Sarma [Phys. Rev. B **40**, 9723 (1989)] show that the main quasiparticle peak contains roughly 60% of the total spectral weight for $k = k_F$. The remainder is in a broad incoherent background.

[14] If Γ is significantly energy dependent, Eq. (2) must be slightly modified.

[15] This analysis ignores the effect of the interlayer charge transfer which occurs when a bias voltage V is applied. This transfer, a result of the capacitance between the 2D sheets, implies that the measured voltage width Γ of the tunnel resonance overestimates the true spectral width by typically 12% in our samples. This small correction has not been applied to the data in Figs. 2 and 3.

[16] The densities, and hence the Fermi energies, are unambiguously determined via the tunneling itself, by observing the quantum oscillations of dI/dV which appear in weak perpendicular magnetic fields.

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