Transport measurements of resonant-tunneling widths

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Using transport measurements, we study resonant-tunneling transmission widths in a series of double-barrier samples grown by GaAs-based molecular-beam epitaxy. We find that the measured apparent resonance width is independent of the barrier and falls in the range of 1–5 meV. We propose two possible explanations: (a) a broadening of the observed width due to well-width variations (i.e., growth islands) across the device mesa or (b) a broadening limited by the electron-impurity scattering in the heavily doped contact regions. The latter has the important implication that the ultimate electron-energy resolution obtained from transport measurement is limited by the intrinsic width due to either inelastic- or even *elastic*-scattering processes in the reservoir.

Double-barrier resonant-tunneling (RT) structures have attracted many researchers because this simple system displays very interesting quantum phenomena as well as many potential applications.[1] Important studies of the basic physical processes have been reported.[2–4] Impressive experiments ranging from detectors up to 2.5 THz (Ref. 5) and quantum-well oscillators up to 420 GHz (Ref. 6) to fabrication of RT transistors[7,8] have been carried out, employing $Al_xGa_{1-x}As$-GaAs structures.

Within the standard theoretical picture,[9] the incident electron is characterized by a plane wave with a well-defined energy. Based on this, one of the most important quantities for resonant tunneling is the width of the resonance, which ideally (i.e., in the absence of scattering processes, for example, by impurities, interface roughness, random alloys, and phonons *within* the double-barrier region) can be calculated in a variety of ways. One can calculate the transmission coefficient versus the electron energy, and then the width is defined by the resonance-transmission line shape; or one can calculate the complex eigenenergy of the double-barrier system, and then the half-width (Γ) is the imaginary part of the eigenenergy which is related to the intrinsic lifetime (τ) of the resonance by $\tau=\hbar/2\Gamma$, and so on. In a real system, however, the resonance width is broadened by scattering processes *within* the double-barrier region. Furthermore, an electrically measured apparent resonance width is broadened by variations of the well width (if present) across the area of the device (nonuniformity broadening). In the present work, we postulate an additional broadening mechanism relevant to electrical (as opposed to optical) measurements, due to self-energy broadening in the contacts. This mechanism is based on the fact that a momentum eigenstate can be defined only in a finite time interval in the contacts; therefore incident electrons cannot be described by perfect plane waves.

In this paper, we use data from transport measurements to infer the resonance transmission width. We start from a simple analytical theory that employs a Breit-Wigner resonance form for the transmission coefficient in the neighborhood of a resonance. We concentrate on the positive-differential-resistance region of the current-voltage (I-V) curve, particularly the onset of the resonant-tunneling current and the subsequent linear part of the I-V curve. The basic idea is that the onset of the RT current corresponds to the resonance line shape of the transmission coefficient crossing the Fermi level in the emitter at low temperature ($k_BT<\Gamma$), where k_B is the Boltzmann constant and T is the temperature. Hence the onset reveals the resonance width Γ, and in addition, the linear part tells us how much of the bias voltage is dropped across the emitter barrier and thus determines the resonance energy relative to the emitter band edge as a function of bias. A typical I-V curve for one of our samples and the schematic double-barrier band-edge profile are shown in Fig. 1.

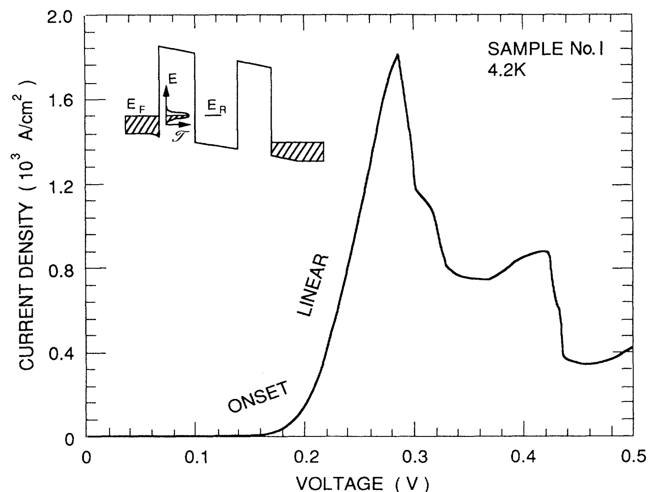

FIG. 1. A typical resonant-tunneling current-voltage characteristic for a 7-μm-diam device. The inset shows the schematic band-edge profile biased in the onset region. The schematic transmission curve ($\mathcal{T}$ vs E) is hatched below the Fermi energy, and the hatched area is proportional to the current.

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The basic theory is reviewed briefly. In the neighborhood of a resonance, the transmission coefficient defined as the ratio of the transmitted and the incident electron flux is given by

$$\mathcal{T} \approx \mathcal{T}_0 \frac{\Gamma^2}{(E-E_R)^2+\Gamma^2} , \quad (1)$$

where E_R is the resonance energy, $\mathcal{T}_0$ is the on-resonance transmission coefficient, which ideally is given by $\mathcal{T}_0 = 4\mathcal{T}_E\mathcal{T}_C/(\mathcal{T}_E+\mathcal{T}_C)^2$, and $\mathcal{T}_E$ and $\mathcal{T}_C$ are the transmission coefficients for the emitter and collector barriers evaluated at the resonance energy. We consider the case where only the emitter-electron Fermi sea contributes to the RT current. To ensure this, we consider only devices where the onset regions of the RT currents occur at bias voltages larger than the Fermi energy in the collectors. The RT current density at zero temperature is then[9,10]

$$J = (em/2\pi^2\hbar^3)\mathcal{T}_0 \int_0^{E_F} dE\,(E_F-E)\frac{\Gamma^2}{(E-E_R)^2+\Gamma^2} , \quad (2)$$

which, after integration, becomes[10]

$$J = (em/2\pi^2\hbar^3)\mathcal{T}_0\Gamma \left\{ (E_F-E_R)\left[\tan^{-1}\left[\frac{E_F-E_R}{\Gamma}\right]+\tan^{-1}\left[\frac{E_R}{\Gamma}\right]\right] - \frac{\Gamma}{2}\ln\left[\frac{(E_F-E_R)^2+\Gamma^2}{E_R^2+\Gamma^2}\right]\right\} , \quad (3)$$

where m is the effective mass in the contacts. For ideal perfectly conducting contacts and for symmetrical double barriers, the voltage (V/e) dependence is $E_R = E_{R0} - V/2$, and E_{R0} is E_R at zero bias. This is the basis for the analysis of our experimental data. We stress that E_R is referenced to the emitter band edge, and hence decreases as the bias is increased. The major bias dependence appears in E_R except in the negative-differential-resistance region where E_R approaches zero and $\mathcal{T}_0$ could vary rapidly. In reality, a non-negligible fraction of the applied voltage is distributed across the emitter accumulation layer and the collector depletion region.[11,12] We introduce a nonideality factor $0 < \alpha \leq 1$ to take these effects into account:

$$E_R = E_{R0} - \alpha V/2 . \quad (4)$$

Since $E_F/\Gamma \gg 1$ and $E_{R0}/\Gamma \gg 1$ are normally satisfied, there exists a linear region in the I-V curve in which $(E_F-E_R)/\Gamma \gg 1$ and $E_R/\Gamma \gg 1$. Equation (3) then becomes

$$J_{\text{linear}} \approx (em/2\pi\hbar^3)\mathcal{T}_0\Gamma(E_F-E_{R0}+\alpha V/2) . \quad (5)$$

Experimentally, this occurs after the onset of the RT current and before the peak current (as shown in Fig. 1).

The double barriers studied here were grown by molecular-beam epitaxy in a VG V80 system. The substrates were either semi-insulating or n-type (Si-doped) (100) GaAs. The epitaxial layer sequence was a bottom contact GaAs layer (Si doped to N_D), an L_S-thick undoped GaAs spacer layer, an L_B-thick undoped $Al_xGa_{1-x}As$ barrier, an L_W-thick undoped GaAs well, an L_B-thick undoped $Al_xGa_{1-x}As$ barrier, an L_S-thick undoped GaAs spacer layer, and finally a top contact GaAs layer (Si doped to N_D). The growth parameters are listed in Table I. A total of seven double barriers were studied, with different barrier and well thicknesses, and alloy fractions. Devices from 7 to 53 μm in diameter were defined by wet chemical mesa etching, and alloyed Ni/Ge/Au contacts were made. I-V curves were recorded with devices immersed in helium at 4.2 K, and some samples were also measured at 1.3 K to confirm that the thermal broadening was negligible and that $k_BT=0$ is a good approximation.

We use the linear portion of the experimental I-V curves to determine $\mathcal{T}_0\Gamma$ and α. The linear part of the experimental I-V curves was fitted by $J = A + BV$ using a

TABLE I. Sample parameters. Parameters are contact doping density N_D, spacer thickness L_S, barrier thickness L_B, barrier Al alloy fraction x, and well thickness L_W.

Sample No.	N_D (10^{17} cm^{-3})	L_S (nm)	L_B (nm)	x	L_W (nm)
1	≈4[a]	4.0	8.7	0.28	4.2
2[b]	≈4[a]	3.8	9.3	0.28	3.8
3	≈4[a]	3.7	3.7	0.42	4.0
4	≈4	4.6	5.1	0.5	4.2
5	≈1	5.0	2.0	1.0	5.0
6	≈1	5.0	2.0	1.0	5.0
7	≈1	5.0	4.0	1.0	5.0

[a]These samples have a graded doping profile from about 2×10^{18} cm^{-3} to N_D.
[b]All GaAs layers are replaced by $In_yGa_{1-y}As$ with $y \approx 10\%$.

linear least-squares scheme. Comparing with Eq. (5), we obtain

$$(em/2\pi\hbar^3)\mathcal{T}_0\Gamma\alpha/2=B\ , \tag{6}$$

$$(em/2\pi\hbar^3)\mathcal{T}_0\Gamma(E_F-E_{R0})=A\ . \tag{7}$$

From Eq. (6), we can obtain a rigorous lower bound of $\mathcal{T}_0\Gamma \geq (em/2\pi\hbar^3)^{-1}2B$ because $0<\alpha\leq 1$, and hence a lower bound of

$$\Gamma \geq (em/2\pi\hbar^3)^{-1}2B \tag{8}$$

because $0<\mathcal{T}_0\leq 1$. From the barrier Al fraction (x) and well thickness, we can determine E_{R0}. The Fermi energy can be estimated using the contact doping, but an error is expected because of (a) the uncertainty in N_D from the epitaxial growth and (b) the accumulation of electrons in the emitter spacer region which effectively increases E_F. From Eqs. (6) and (7), α and $\mathcal{T}_0\Gamma$ are determined. We then use these values with Eq. (3) to find a fitted Γ (using a least-squares scheme to fit the experimental onset region). The lower bound of Γ computed using Eq. (8) and the fitted Γ are plotted in Fig. 2 versus a parameter called "barrier strength," which characterizes how transparent a barrier is. The barrier strength is defined as $L_B[m'(U-E_{R0})]^{1/2}$, where U is the barrier height and m' is the (dimensionless) reduced effective mass in the barrier. Results for Γ from an ideal complex-eigenenergy calculation are also shown in Fig. 2 (solid line). Note that the lower bound of Γ given here is purely experimental and is independent of any growth parameters. Furthermore, the fitted Γ depends only on E_F and E_{R0}, and we use estimated errors in E_F to generate the vertical error bars in Fig. 2. The horizontal error bars are due to the uncertainty in barrier widths. The values of E_F around the onset have been calculated using a self-consistent scheme.[11,12] We point out that the barrier strength for sample No. 7 is obtained assuming a barrier height determined by the direct band offset of about 1 eV. Since the AlAs barrier thickness for this sample is 4.0 nm, Γ-X mixing becomes important,[13] effectively reducing the barrier strength. This would move the lower bound for sample No. 7 much closer to the ideal calculation. From the slope of the *I-V* curves, we determine experimentally $\mathcal{T}_0\Gamma\alpha$ [Eq. (6)]. For the simple theory to be consistent, a lower bound on Γ [Eq. (8)] obtained by assuming $\mathcal{T}_0\alpha=1$ should be less than or equal to the value of Γ obtained from a complex-eigenenergy calculation. As can be seen from Fig. 2, the measured lower bounds show that the theory is quite consistent.

From Fig. 2, it is clear that the measured apparent resonance width is much greater (many orders of magnitude in some cases) than that obtained from an ideal calculation. The less transparent the barrier is, the larger is the deviation. In fact, the width appears to be independent of the barrier strength and has a value in the range of about 0.8–4.6 meV. To verify that the thermal broadening has no effect, some devices (sample Nos. 1, 2, and 3) were measured at a lower temperature of 1.3 K. The resonance width we measure here is apparently not the width associated with the intrinsic resonance lifetime, which has been measured directly by time-resolved optical techniques.[3,14] In those experiments, the intrinsic resonance *lifetime* was measured because the electrons were directly created *in* the well from the valence band, and the time needed for electrons to leak out was independent of the regions outside the double barrier. Therefore those measurements gave a width that followed an ideal calculation like the line shown in Fig. 2. Our measurement, on the other hand, gives the transport width, which *is* affected by scattering within the double-barrier region but may *also* be affected by scattering processes *outside* this region.

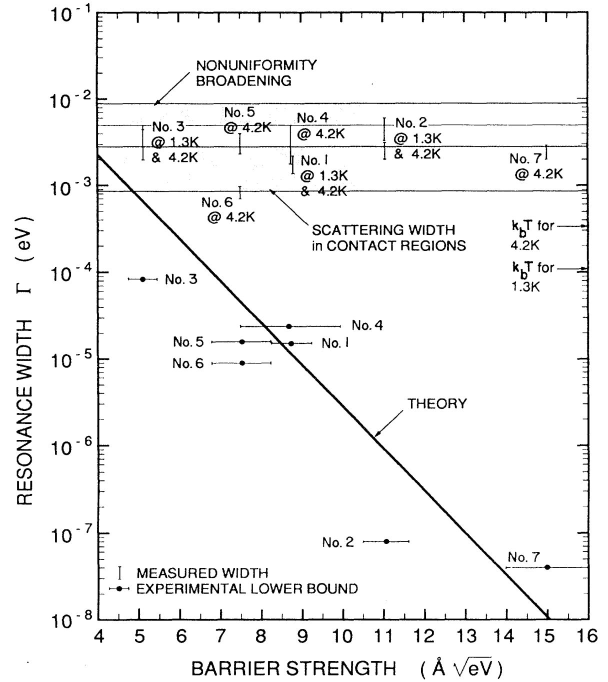

FIG. 2. The experimental lower bound, the fitted and the theoretical resonance widths Γ vs barrier strength (defined as the barrier width multiplied by the square root of the effective barrier height and the effective mass in the barrier). The theoretical calculation neglects scattering processes. The upper shaded band represents the range of broadening due to a monolayer variation in well width over 50% of the tunneling area. The lower band represents the broadening due to scattering effects in the contacts.

To understand our data, we first consider the effect of scattering *within* the double barrier. Scattering by optical phonons gives rise to sidebands separated from the main resonance transmission peak by the phonon energy and does not broaden the main resonance transmission substantially.[15,16] The interface roughness broadening is expected to be less than about 0.3 meV.[17] Calculations[18] show that the broadened resonance width is about 0.2 meV, including scattering by optical phonons, interface roughness, alloy disorder, and acoustic phonons. This cannot account for our experiment, and, in fact, in optical experiments[3,14] much smaller widths were observed. We therefore propose the following two possibilities.

First, if growth islands occurred at heterointerfaces, our quantum wells would have large-scale (greater than about 1000 Å) lateral variations in well widths across the device mesas. We would then expect a broadening of about the resonance-energy change when the well width is changed by a monolayer ($\sim$2.8 Å). We make a distinction between interface roughness and islands. The former is expected to involve lateral variations on a scale much smaller than 1000 Å.[17] The calculated change in resonance energy corresponding to a monolayer well-width change for our samples ranges from 5 to 9 meV. This range is shown in Fig. 2 as the upper band. We point out that this well-width nonuniformity broadening is an estimate based on the assumption that the device area consists of approximately equal areas with a monolayer difference in well width. In reality, a broadening larger or smaller than 5–9 meV is possible. If this mechanism were strongly involved, it would be rather surprising, but not impossible, that the samples studied here all had characteristic nonuniformity broadening in the narrow range observed here, rather than broadenings spread out over a large energy range including the upper band of Fig. 2. Secondly, we consider the scattering processes *in* the contacts that give rise to an intrinsic width associated with an incident electron from the reservoir. Since the contact region is heavily doped with donor impurities (Si in our case), the electron-impurity Coulomb scattering dominates the width. The intrinsic width Γ_s is the imaginary part of the single-particle self-energy function, and is related to the relaxation time by $\tau_s = \hbar/2\Gamma_s$ which is a measure of the time in which an electron momentum eigenstate can be defined.[19] Therefore an electron incident on the double barrier cannot in reality be described by a perfect plane wave. The impurity-limited low-temperature mobilities for the doping densities of our samples are estimated to be in the range $\mu = (3-10) \times 10^3$ $cm^2/V\,s$.[20] For the three-dimensional case and for our doping densities, the relaxation time and the mobility scattering time are roughly the same.[19] Using $\mu \approx e\tau_s/m$, the intrinsic width Γ_s is then about 0.86–2.87 meV. This range is drawn as the lower band in Fig. 2. The measured resonance widths Γ fall within the range of Γ_s and slightly below the well-width nonuniformity broadening.

An obvious question is whether there is a way of distinguishing between the two mechanisms. Experimentally, the detailed structures of heterointerfaces are not known.[21] Some optical experiments[22] suggest that under certain growth conditions large-lateral-scale islands occur, but there appears to be some disagreement[21] about such an interpretation. A special transmission-electron-microscopic technique[23] suggests that small-lateral-scale interface roughness is also possible. If the second mechanism were strongly involved, one might want to change the doping density in the contacts and correlate the change in resonance width with the change in doping. However, our measured resonance width is only accurate to within a factor of about 3 as shown by the errors bars in Fig. 2. The error is mainly caused by the uncertainty in doping. Indeed, the doping concentration in the emitter immediately before the double barrier is not known experimentally to better than a factor of 2 or more, as indicated by the $\approx$ sign in Table I. To accurately characterize the doping concentration in the (thin) relevant region is extremely difficult. Thus, within the accuracy of our experiment we cannot correlate doping density and the resonance width quantitatively for our samples, which have at least a factor-of-4 difference in doping densities. If we reduce the doping density to much lower than 10^{17} cm^{-3}, effects associated with the strongly triangular-shaped potential profile in the accumulation layer will complicate the onset region of the experimental *I-V* curves.[24] Furthermore, the change in electron mobility obtained from a change of doping density from 4×10^{17} to 2×10^{19} cm^{-3} is less than a factor of 2.[25] Hence increasing the doping will not produce enough change in measured resonance width to be detected experimentally. Another, and more fundamental, uncertainty is related to where exactly the contact (electron reservoir) "starts." For example, the electron reservoir cannot start immediately outside the double barrier because spacer layers are not expected to have a substantial amount of doping and the electron phase-breaking length is certainly longer than the spacer-layer thicknesses.

In conclusion, we have measured the resonant-tunneling transmission width in a series of double-barrier structures. The measured width is much larger than that predicted by the standard model even when scattering processes *within* the double-barrier region are included. We propose two possible explanations: (a) an inhomogeneous broadening related to lateral well-width nonuniformity, or (b) the intrinsic width of the incident electron from the reservoir related to the electron relaxation time, which gives rise to a finite single-particle width. The latter, if correct, imposes a fundamental limit on the electron-energy resolution in transport measurements. This has been neglected in the standard theoretical approach in calculating vertical transport characteristics.[9,10] The mechanisms would also limit the resolution in experiments on electron spectroscopy.[26,27]

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