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# Electron-transport dynamics in quantized intrinsic GaAs

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Information on the self-energy of quantized current-carrying electron states in intrinsic GaAs has been obtained. The lifetime of Γ electron states in double-barrier resonant-tunnel structures depends on the well width, longitudinal optical phonon scattering, and transfer into the subsidiary $X$ and $L$ minima. Application of a magnetic field parallel to the direction of current injection totally quantizes the electronic system and enhances the lifetime of low-energy electron states.

There exists little empirical information about nonequilibrium electron-transport dynamics via quantized electron states in intrinsic semiconductors. In this paper we present new experimental data on the self-energy of current-carrying, two-dimensional electron states in GaAs. In addition, we explore the effect of total quantization by applying a magnetic field.

Double-barrier resonant-tunnel structures[1] [see Fig. 1(a)] were fabricated on ⟨100⟩-oriented semi-insulating GaAs substrates using molecular-beam epitaxy. After forming an $n$-type ($n = 1\times10^{18}$ cm$^{-3}$ Si impurity) GaAs buffer layer on the substrate, a 45-Å-thick AlAs barrier layer was deposited. A low crystal-growth temperature of 560° C was used to minimize problems associated with diffusion of Si impurities into the tunnel barriers. A layer of intrinsic GaAs with thickness in the range 100 Å $< z_o <$ 700 Å was then grown to form the quantum well. Following this a 45-Å-thick AlAs layer and a 3000-Å-thick $n = 1\times10^{18}$ cm$^{-3}$ GaAs cap layer was deposited to complete the structure. After removal from the growth chamber the wafer was etched into mesas and separate Ohmic contacts were made to the two $n$-type regions. The electrical measurements reported here were made with samples maintained at a temperature of 4.2 K. Mesas of differing areas were used to eliminate the possibility of spurious edge effects and high-resolution transmission-electron microscopy was used to accurately determine $z_0$ and the thickness of the AlAs barriers.

Under a voltage bias $V_c$, the Γ conduction-band minimum has a profile similar to that shown in Fig. 1(a). Electrons moving in the $z$ direction from the $n$-type region on the left-hand-side first encounter the AlAs tunnel barrier of energy $\phi_0 = 1.3$ eV. Electrons contributing to current tunnel through this barrier, accelerate attaining a

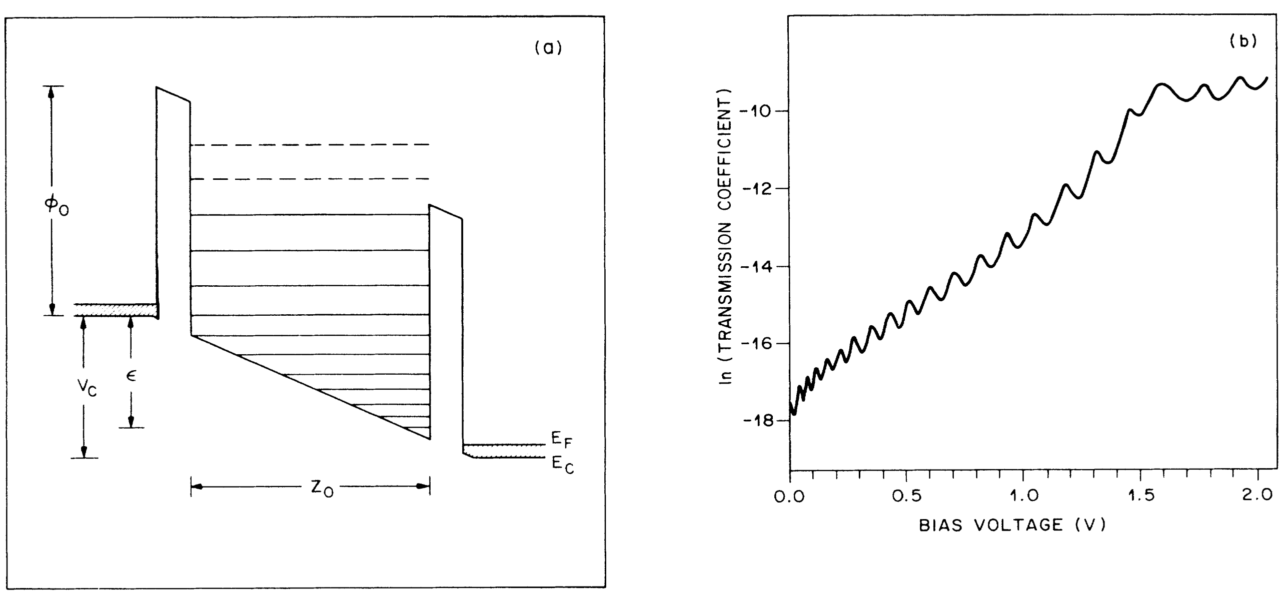


FIG. 1. (a) Schematic diagram of the conduction-band edge $E_c$ of a double-barrier resonant-tunnel structure under a bias voltage $V_c$. The AlAs barrier has energy $\phi_o$, the GaAs well width is $z_0$, energy levels are shown as horizontal lines, and the maximum energy of an electron in the well is $\epsilon$. $E_F$ is the Fermi energy of the $n$-type GaAs. (b) Calculated logarithm of the transmission coefficient as a function of voltage bias for the structure shown in (a). An effective mass of $m^* = 0.07m_0$ for GaAs and a well width $z_0 = 450$ Å was used for the calculation.

 

maximum energy $\epsilon$ in the quantum well, and tunnel through the second right-hand tunnel barrier. The electron tunneling probability increases exponentially with decreasing effective barrier energy $\phi_{\text{eff}}$. For certain values of bias $V_c$, the conduction-band minimum in the left-hand $n$-type region aligns with one of the discrete energy levels in the quantum well. When this occurs there is a resonant enhancement in the amount of current flowing through the structure. In the absence of electron scattering in the quantum well, the contribution to current from both resonant and nonresonant processes increases exponentially with applied voltage bias because the effective energy of the second barrier decreases approximately as $\phi_{\text{eff}} \sim (\phi_0 - eV_c)$. At a voltage bias larger than $\phi_0$ current flow is limited by the first tunnel barrier and resonant enhancement in current can only occur via virtual states. This behavior may be illustrated by calculating the electron transmission coefficient assuming a parabolic conduction band, i.e., within the effective-mass approximation.[2] In Fig. 1(b) we plot the logarithm of transmission coefficient with applied bias $V_c$ for a well width, $z_0 = 450$ Å. The finite Fermi energy $E_F$ of the $n$-type region has been included in the calculation. As may be seen, with increasing $V_c$ the calculation reveals an exponential increase in the oscillatory resonant behavior superimposed on an exponentially increasing nonresonant background. For $V_c \gtrsim 1.3$ V the oscillations are damped due to transport through energetically broad virtual states and transmission probability is essentially limited by the first tunnel barrier.

Deviations from this simple picture occur in a real solid due to the finite lifetime of electronic states and nonparabolicity of the conduction band. As the electron traverses the quantum well it may scatter, thereby damping the resonance. This damping broadens and reduces the amplitude of conductance oscillation.[3] Nonparabolicity, on the other hand, decreases the period of the conductance oscillations compared to the calculated value at large $V_c$.

In Fig. 2(a) we show results of measuring the logarithm of conductance $\ln(dI/dV_c)$ as a function of applied voltage bias $V_c$ for structure with well width $z_0 = 450$ Å. The use of thick AlAs tunnel barriers ensures that current densities are low so that space charging effects[4] are unimportant in our structure. We also note that we have not observed any effects associated with subsidiary $X$-minima resonant tunneling.[5,6] As may be seen in Fig. 2(a), at low voltage bias the amplitude of conductance oscillations is heavily damped. The oscillation period at around 400-mV bias is 60 mV and should be compared with the value of 75 mV calculated using the effective-mass approximation [see Fig. 1(b)]. This discrepancy arises due to conduction-band nonparabolicity in GaAs and could, in principle, be used to *measure* the semiconductor band structure. For example, in effective-mass theory the oscillation period scales approximately as $1/m^*$ (where $m^*$ is the electron's mass) implying an $\sim 25\%$ increase in $m^*$ at 400 mV. With increasing $V_c$ the amplitude of the conductance oscillations increases to a maximum at around $V_c \simeq 500$ mV, beyond which the intensity of the oscillations begins to decrease. This effect is observed in all samples with well widths ranging from $z_0 = 350$ to 700 Å but *not* for $z_0 \lesssim 200$ Å. In this latter case the behavior is qualitatively similar (apart from a reduced oscillatory period) to the predictions of the naive effective-electron-mass model discussed above.

Our experimental results may be summarized by plot-

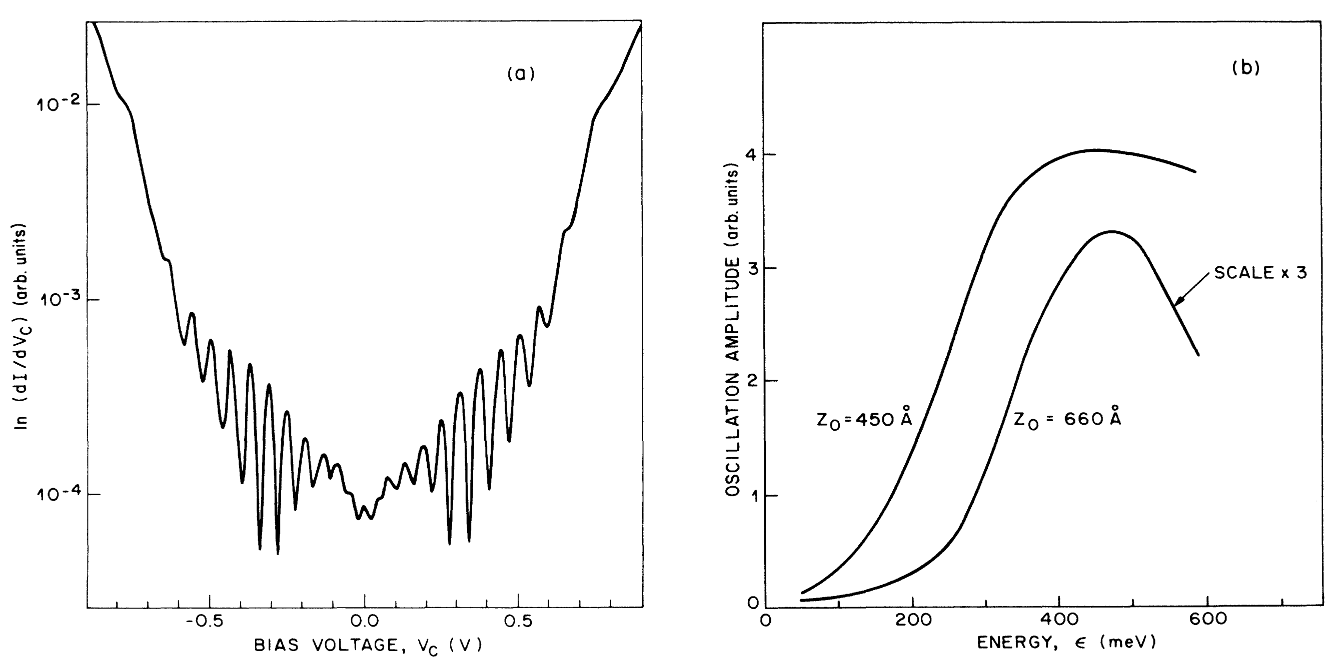


FIG. 2. (a) Measured logarithm of conductance with applied voltage bias for a double-barrier resonant-tunnel structure with a well width $z_0 = 450$ Å. (b) Amplitude of conductance oscillations as a function of $\epsilon$ for samples with $z_0 = 450$ and 660 Å.

ting the amplitude of $dI/dV_c$ oscillation with maximum energy $\epsilon$ attained by the electron in the quantum well. Results are given in Fig. 2(b) for two samples differing only in well width $z_0=660$ Å and $z_0=450$ Å. For values of $\epsilon<300$ meV, the lifetime $\tau$ for electrons in the well is dominated by $\hbar\omega_{LO}=36$ meV longitudinal optic-phonon emission [for an electron of energy greater than $\hbar\omega_{LO}$ in bulk GaAs the phonon scattering rate is approximately constant at around $1/\tau_{ph}\sim5\times10^{12}$ $s^{-1}$ (Ref. 7)]. Very approximately, if the time an electron spends in the well is $t$, then the probability of scattering is proportional to $1-\exp(-t/\tau)$. Because $t$ decreases with increasing $\epsilon$, a rapid increase in $dI/dV_c$ oscillation amplitude is observed with increasing $\epsilon$. We have also found that, for fixed $\epsilon$ and $z_0$, $t$ may be reduced by decreasing the thickness of the AlAs barriers.

For values of $\epsilon\gtrsim350$ meV, scattering into the subsidiary $L$ minimum of GaAs is also possible and for $\epsilon\gtrsim460$ meV the conductance oscillation amplitude is dominated by transfer into the subsidiary $X$ minimum [in bulk GaAs this scattering rate is $1/\tau_{tr}\sim2\times10^{13}$ $s^{-1}$ (Ref. 7)]. These trends are clearly demonstrated by the data in Fig. 2(b) for the 660-Å wide well.

For $z_0=450$ Å, the amplitude of conductance oscillations is more than a factor of 3 greater than the $z_0=660$ Å case [see Fig. 2(b)]. We note that the quantization energy $\Delta_i$ between the $i$th and $(i+1)$th energy level of electron states in the well ($\Delta_i\sim$oscillation period) affects electron scattering rates. The increased quantization energy, $\Delta_i$ for a narrow well reduces scattering rates because of restrictions imposed on the type and number of final states into which an electron can scatter. For example, the probability of polar optic phonon emission decreases with increasing scattered wave vector $q$, so that for $\Delta_i\gg\hbar\omega_{LO}$ there are few $q\simeq0$ transitions and resultant suppression in phonon emission probability.[8] Hence, scattering rates become less important in determining the current-voltage characteristics of our resonant-tunnel structures for well widths less than around 200 Å. In this situation a modified effective-mass theory may be used to model resonant electron transport in the structure.

To study the effect *total* quantization of electronic states has on electron self-energy, we applied a magnetic field parallel to the direction of current injection. The well, of width $z_0$, quantizes electronic states in the $z$ direction with quantization energy $\Delta_i$, and the magnetic field quantizes in the $x$-$y$ plane with energy $\hbar\omega_c$, where $\omega_c$ is the cyclotron frequency.[9] Typical results of our measurements on a sample with $z_0=450$ Å are shown in Fig. 3. With no applied magnetic field, conductance oscillations shown as the broken line are observed. In a magnetic field of 8 T ($\hbar\omega_c\simeq13$ meV), there is an enhancement in oscillation amplitude (solid line in Fig. 3) over the zero-field result at low-voltage bias. This enhancement in oscillation amplitude is related to an increase in $\tau$ and occurs because of restrictions in the number of final states electrons can scatter into.[10] Since scattering contributes a width $\delta=2\pi\hbar/\tau$ to the current oscillation, a value for $\tau$ may be obtained from the data. For example, a fit to the data between $V_c=150$ and 200 mV gives $\tau\sim200$ fs in zero magnetic field and $\tau\sim260$ fs at 10 T. This time is an order of

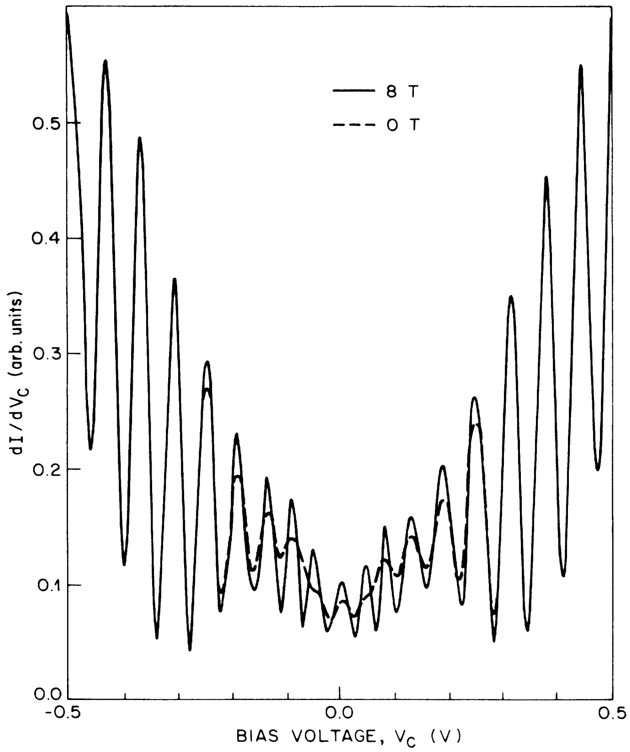


FIG. 3. The effect a magnetic field of 8 T applied parallel to direction of current injection (solid line) has on the conductance data for a sample with $z_0=450$ Å. The zero magnetic field results (broken line) are also shown for comparison.

magnitude less than the calculated zero-field lifetime of the state in the absence of scattering and serves to illustrate the importance electron scattering has in determining the amplitude and shape of the conductance oscillations. At larger voltage bias the $dI/dV_c$ curves with and without magnetic field merge to a common value. The decrease in $\tau$ to the zero-field value occurs because at high energies there are a large number of subbands into which an electron may scatter. This is, in essence, a sum rule forcing electrons with $\epsilon\gg\hbar\omega_c$ to have the same scattering rates as without a magnetic field. Finally, we note that application of a large magnetic field perpendicular to the direction of current injection has the expected effect of damping the amplitude of $dI/dV_c$ oscillations.

To conclude, we have performed a series of experiments which probe the self-energy of quantized current-carrying states in intrinsic GaAs. We demonstrated that finite lifetime effects and a realistic description of the GaAs band structure are important to correctly model electron transport in double-barrier resonant-tunnel structures. In addition, by applying a magnetic field we were able to show that the lifetime $\tau$ of low-energy states is significantly enhanced in a totally quantized electronic system.

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[8]For hot-electron transport across a quantum well containing mobile charge carriers, the physics determining scattering rates is complicated by the many-body response of the system. The important (competing) effects are first, a reduction compared to the three-dimensional case, in screening which increases scattering rates and second, small scattering angles, typical of Coulomb scattering, which decrease scattering rates for perpendicular transport [see A. F. J. Levi and T. H. Chiu, Appl. Phys. Lett. **51**, 984 (1987)].

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[10]S. Schmitt-Rink (private communication) has shown theoretically that this is so for bulk states in GaAs. The results of these calculations are in qualitive agreement with our observations in a two-dimensional electronic system.