Analysis of resonant-tunneling transport

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We analyzed the properties of the two factors determining the resonant-tunneling transport: the one-dimensional carrier energy distribution factor, which monotonically decreases with energy and increases with temperature, and the transmission probability peak, which decreases with bias and temperature, and we determined a criterion for current resonance. Our conclusions are quite different from those in commonly used descriptions. Calculations of the resonant tunneling versus temperature with constant E_F, μ, and m^* cannot give a decrease of peak currents with temperature. When effects of the E_F position and the changes of E_F, μ, and m^* with temperature are considered, the experimental results, e.g., both increasing and decreasing peak currents with temperature, can be explained in a coherent way.

I. INTRODUCTION

Resonant tunneling has attracted great interest in experimental[1-8] and theoretical[8-12] studies. All experiments on resonant-tunneling structures (RTS's) have shown that the resonant-tunneling features weaken with increasing temperature: the current peak-to-valley ratio decreases and the negative differential resistance gradually disappears.[1-8] Previous experiments show that the valley current always increases, while the peak current can decrease[3-5] or increase[5-7] with temperature. Our recent experiments on SiGe/Si RTS's demonstrated that valley current can also decrease with increasing temperature in certain cases.[5] On the other hand, the published theoretical analyses show that the valley current should increase, and the peak current could increase[9,12] or decrease[11] with temperature. The reasons for these different variation tendencies have not been fully understood so far, and the proposed analyses have been unable to explain the experiments in a consistent scheme. In fact, up to now, the three-dimensional (3D) carrier-energy distribution function (CEDF) is often directly used to discuss the origin and properties of resonant tunneling which is essentially a 1D transport phenomenon. An insufficient understanding of the properties of the 1D CEDF, which is a governing factor in the resonant-tunneling transport, can lead to erroneous conclusions as discussed below. At the same time, it has not been recognized enough that the transmission peak value decreases with the applied bias, and also with temperature due to scattering. In this Brief Report we will discuss the characteristics of the 1D CEDF and transmission probability, propose the criterion of resonance, analyze the effects of Fermi level E_F, effective mass m^*, and carrier mobility μ, and calculate the resonant-tunneling characteristics and the temperature dependences.

II. GENERAL ANALYSIS

A. 1D CEDF $g(E)$, transmission probability $\mathcal{T}_T(E)$, and the resonance criterion

For a double-barrier resonant-tunneling structure (DBRTS) with parabolic band structures [Fig. 3(a)], the perpendicular transport current is[1,8,9]

$$J=\frac{2q}{(2\pi)^3}\int \mathcal{T}_T(E)[f(E)-f(E+qV)]\mathbf{v}(\boldsymbol{\kappa})d\boldsymbol{\kappa} \; . \tag{1a}$$

Here the group velocity $\mathbf{v}(\boldsymbol{\kappa})=(2\pi/h)\nabla_k E$. Under the parabolic-band assumption the transverse currents are zero due to symmetry. By changing the variable of integration from momentum to energy, the longitudinal current can be derived:

$$J_x=J=\int_0^\infty \mathcal{T}_T(E)g(E)dE \; . \tag{1b}$$

Here the symbol E in Eq. (1b) means E_x, the energy component corresponding to κ_x, but for simplicity we omitted the index. We have defined a 1D CEDF as

$$g(E)=\frac{4\pi q m^* kT}{h^3}\left\{\ln\left[1+\exp\left[-\frac{E-E_F}{kT}\right]\right]-\ln\left[1+\exp\left[-\frac{E+qV-E_F}{kT}\right]\right]\right\}, \tag{2}$$

where $g(E)$ is the integral of the Fermi-Dirac distribution function $f(E)$ over the 2D $\boldsymbol{\kappa}$ space parallel to the interfaces. $g(E)$ monotonically decreases with energy and monotonically increases with temperature for all energies (Fig. 1). For large E_F, $g(E)$ increases slowly with tem-

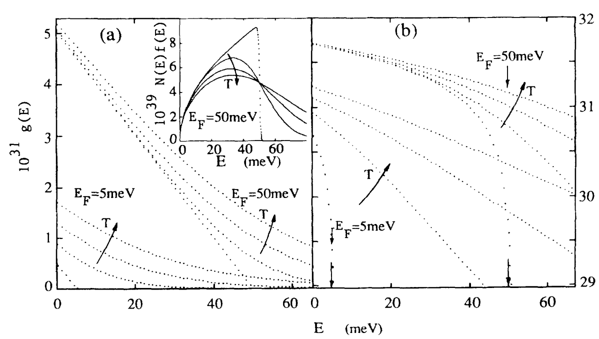

FIG. 1. The 1D CEDF, $g(E)$, and $\log_{10}[g(E)]$ vs E for $V=0.2$ V and $T=4.2$, 100, 170 and 240 K, which increases along the arrow. The inset is the 3D CEDF [i.e., $N(E)f(E)$] vs E. For generality we use $m^*=m_0$ here. For any material, $g(E)$ can be obtained by using m^* instead of m_0.

perature at energy $E \ll E_F$. For small E_F, however, $g(E)$ increases fast with temperature, particularly for the part above E_F. These characteristics are very different from the 3D CEDF, $N(E)f(E)$. In the inset of Fig. 1 it is seen that the normal 3D CEDF is a peaked function of energy, and for constant E_F and m^* it monotonically decreases with increasing temperature for energies $E < E_F$. Some authors have directly used the 3D CEDF to analyze the transport of RTS's and to define the condition when a resonance should occur. A commonly described picture is that of a resonance that occurs when the subband (i.e., the energy of a transmission peak) is moved to an energy aligned with E_F, or conduction-band edge E_c, or the maximum position of the 3D CEDF. Then the peak current has been expected to decrease with temperature, since the maximum value of the 3D CEDF is smaller at higher temperature.[11] This is incorrect because the perpendicular transport of RTS's is not determined by the 3D CEDF, but by the 1D CEDF [Eqs. (1)]. It will be shown later that, at the current peak maximum, the subband position can be much higher or lower than E_F, depending on the E_F position, temperature, and the device structure parameters (Fig. 3).

Figure 2(a) shows that a transmission peak value $\mathcal{T}_p$ is reduced monotonically by increasing bias, particularly for high bias when the subband is located close to the band edge at the emitter interface (defined as the emission region–first barrier interface). The symmetry of a RTS is then severely distorted and finally the transmission peak disappears. Considering the influence of the scattering i.e., the temperature dependence of the mobility, the $\mathcal{T}_p$ also decreases monotonically with temperature [Fig. 2(b)], as discussed later.

Under bias, the subband level $E = E_n$ shifts towards lower energy and $\mathcal{T}_p$ decreases, while the magnitude of $g(E)|_{E_n}$ increases. The balance between the decreasing trend of $\mathcal{T}_p$ and the increasing trend of $g(E)|_{E_n}$ with bias determines at what bias the tunneling current reaches its maximum [see Eqs. (1)]. This is the true criterion of resonance. This condition, i.e., resonant tunneling, takes place when the current gain due to the relative rise of $g(E)$ is canceled out by its loss due to the relative drop of the product of $\mathcal{T}_p$ and its full width at half maximum,

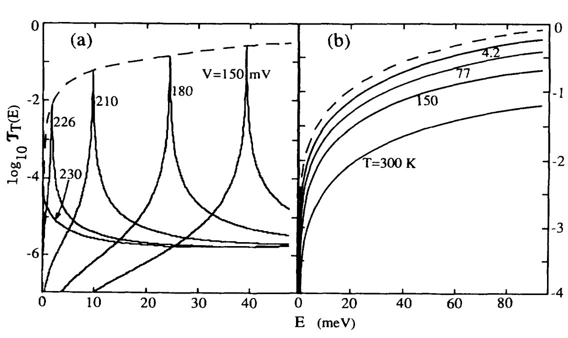

FIG. 2. (a) Transmission probability $\mathcal{T}_T(E)$ vs E for different bias and (b) the first peak transmission $\mathcal{T}_p$ vs E for different temperatures in a RTS as described in Fig. 3(a). The dashed line is $\mathcal{T}_p$ vs E without scattering influence.

$\Delta E_{\mathcal{T}_p}$, can be formulated as

$$\left[\frac{1}{g(E)}\frac{dg(E)}{dE}\right]\Bigg|_{E_n} = -\frac{1}{\mathcal{T}_p \Delta E_{\mathcal{T}_p}} \frac{d(\mathcal{T}_p \Delta E_{\mathcal{T}_p})}{dE} . \quad (3)$$

This criterion is valid provided that the higher-order subband tunneling is not very important. The same condition also determines the subband position at resonance, the resonance peak voltage, and the other characteristics of RTS's.

B. Results obtained assuming constant E_F, μ, and m^*

If we take a close look at the variations of $g(E)$ and transmission with temperature, energy, and bias [Figs. 1 and 2(a)], we find that for any energy assuming E_F, μ, and m^* are constant (do not change with temperature or bias) as temperature increases, the transmission does not change, but $g(E)$ increases monotonically (Fig. 1), so it is impossible for the peak or valley current to decrease with temperature. In other words, the explanations that the peak current decreases with temperature due to the drop of the maximum value in the 3D CEDF (Ref. 11) or due to a small m^* value[7] are incorrect. The results of our calculations of peak and valley currents assuming constant E_F, m^*, and μ can be summarized as follows [see Fig. 4(a)]. For high E_F, peak and valley currents increase slowly with temperature, especially in the low-temperature region, because the resonant subband energy $E_{np} \le E_F$ and $g(E)$ increases slowly with temperature. For low E_F, $E_{np} > E_F$ in general, and $g(E)$ increases very fast with temperature, so the peak current increases fast with temperature, but the valley current increases even faster because its main part comes from carriers tunneling via the high-energy part of the transmission spectrum, corresponding to the high-energy part of $g(E)$, which increases with temperature more strongly (Fig. 1).[12]

C. Some temperature-dependent physical parameters: E_F, μ, and m^*

1. Fermi energy E_F

E_F is a function of temperature and bias. For a DBRTS with spacer layers as shown in Fig. 3(a), the contact region is usually highly doped. The spacers and the active region are intrinsic or low doped. When applying a bias, E_F in the contact region stays approximately constant, but in the emission region it splits into the electron/hole quasi-Fermi-levels E_{Fn}/E_{Fp}. Since the bias induces band bending and carrier accumulation in the emission region, the E_{Fn} [meaning the magnitude of E_{Fn} relative to E_c $(=0)$ at the emitter-first barrier interface] becomes larger. E_{Fn} can, in principle, be calculated by solving the Poisson equation and the Schrödinger equation self-consistently. To reduce the calculation effort, we make the assumption that it is possible to get an approximate value *at current resonance* at T K, from its value at 0 K, E_{Fn}^0 (Fermi-level parameter), by solving the Poisson equation. The change due to the finite temperature is estimated from the charge-neutrality condition for the degenerate case. In the following calculations, E_{Fn}^0 is used as an input parameter simulating the different RTD structures.

2. Scattering effects

In many published results, the incident and the reflected waves are assumed to be coherent[1-3,8-12] and the transmission peak probability should be unity at zero bias. Such an assumption can only be valid when all kinds of scattering (elastic and inelastic) can be neglected. In other words, the intrinsic resonance width $\Delta E_{\mathcal{T}_p}$ has to be much larger than the scattering-induced broadening ΔE_s. Usually, the scattering destroys the coherence of the electron waves and decreases the transmission probability $\mathcal{T}_T(E)$.[13] The relation of $\mathcal{T}_T(E)$ to the perpendicular transport mobility μ_w and the effective mass m_w^* of the 2D carriers in the quantum well can be derived as

$$\mathcal{T}_T(E)=\Delta E_{\mathcal{T}_p}\left[4(E-E_n)^2\left[\Delta E_{\mathcal{T}_p}+\frac{hq}{m_w^*\mu_w}\right]^{-1}+\Delta E_{\mathcal{T}_p}+\frac{hq}{m_w^*\mu_w}\right]^{-1}, \qquad (4)$$

and then the transmission peak value is

$$\mathcal{T}_p=(1+\Delta E_s/\Delta E_{\mathcal{T}_p})^{-1}=\left[1+\frac{hq}{m_w^*\mu_w\Delta E_{\mathcal{T}_p}}\right]^{-1}. \qquad (5)$$

Only when the barriers are thin and low is the well width small and μ_w high, i.e., when $\Delta E_{\mathcal{T}_p}$ is much larger than ΔE_s, the scattering can be neglected. The values of the perpendicular transport mobility μ_w are still lacking, while for some structures we know the values for the lateral direction, e.g., the lateral mobility in a GaAs/$Ga_{1-x}Al_xAs$ 2D quantum well.[14] For a first estimate, we assume that those values, which decrease with increasing temperature, can be used in our perpendicular transport case. From Eq. (5), it is found that, as an effect of the scattering, the peak transmission monotonically decreases with temperature. The result for the first transmission peak value is shown in Fig. 2(b). The impact of scattering on the peak current or on the *I-V* characteristics should thus vary with temperature and it is also closely related to the intrinsic transmission resonance width $\Delta E_{\mathcal{T}_p}$. Therefore, RTS's with different structure parameters and material properties will not only have different *I-V* features, but also different temperature dependences.

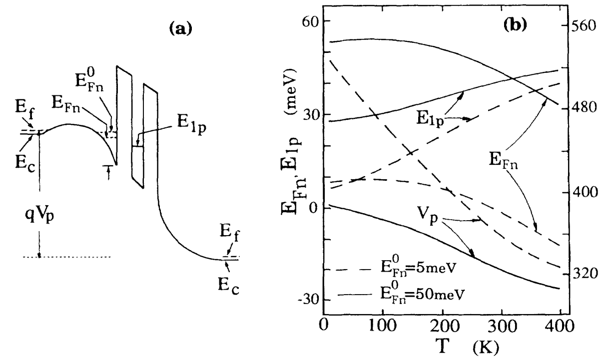

FIG. 3. (a) Schematic diagram of the conduction band and energy parameters of a $Ga_{1-x}Al_xAs$/GaAs electron DBRTS. Here $x=0.5$, barrier width $b_1=b_2=40$ Å, well width $w=50$ Å, and spacer thickness $L_s=150$ Å. (b) E_{FN}, E_{1p}, and V_p at resonance vs T for the same RTS as in (a). The temperature dependence of E_F, μ, and m^* has been considered in the calculations. Here V_p indicates the voltage drop over the active region.

3. Effective mass m^*

As is known, m^* is a function of temperature. In SiGe/Si RTS's, the hole effective mass increases with temperature,[15] resulting in an increase of $g(E)$ and a decrease of the transmission. But in $Ga_{1-x}Al_xAs$/GaAs RTS's, the situation is the opposite: the electron effective mass decreases with temperature,[16] resulting in a decrease of $g(E)$ and an increase of the transmission. Our calculations show that its influence on transmission is, in general, more important, and it will significantly influence the transport characteristics.

Other parameters, such as band gap, electron affinity, and dielectric constant all vary with temperature. While also they influence the resonant-tunneling transport, the effects are minor and will not be discussed here.

III. RESULTS AND DISCUSSION

Taking into account the temperature variations of E_F, μ, and m^*, we have calculated the transport properties and their temperature dependence for GaAs/$Ga_{1-x}Al_xAs$ electron RTS's.

Figure 3 shows that the first subband position E_{1p} *at resonance* is a function of temperature and E^0_{Fn}. The structure parameters used are described in the caption of Fig. 3(a). E_{1p} can be much lower or higher that E_{Fn}, unlike in the 3D CEDF description, where E_{1p} should be aligned to or very near E_{Fn}. The conclusions are also valid for higher-order resonances. As the bias increases, the subbands move to lower energies and $g(E)$ increases. The rate of increase of $g(E)$ is large when $E>E_{Fn}$, but it becomes smaller as $E<E_{Fn}$. This change is stronger when the temperature is low [Fig. 1(b)]. At the same time the transmission peak value decreases initially slowly, then faster [Fig. 2(b)].

For large E^0_{Fn}, the drop of the transmission peak value with decreasing energy is not very significant at $E\sim E_{Fn}$ [Fig. 2(b)]. At low temperature, the current resonance takes place when the subband is brought to much lower energy than E_{Fn} and the relative gain of $g(E)$ is balanced by the relative decrease of transmission, as shown by Eq. (3). However, E_{1p} is still much higher than the band edge due to the large E^0_{Fn} value (and therefore, the low peak-voltage value). With increasing temperature, the peak voltage will decrease and the E_{1p} position will increase slowly, since $g(E)$ varies less [Fig. 1(b)].

For smaller E^0_{Fn}, at low temperature, E_{1p} is small and the peak voltage is large due to the fast increase of $g(E)$ with energy, which *at resonance* should be compensated by a fast decrease of the transmission peak (requiring small E_{1p}) according to Eq. (3). At higher temperature, E_{1p} is much higher than E_{Fn} and the peak voltage decreases due to the slower change of $g(E)$. The rate of both the E_{1p} increases and peak voltage decreases with temperature is larger than that for larger E_{Fn}^0 [Fig. 3(b)]. For the same reason, the valley voltage also decreases with temperature and the rate of change is higher. The rate difference of E_{1p} increasing and peak voltage decreasing with temperature between large and small E_{Fn}^0 is mainly due to the difference in the rate of increase in $g(E)$ between these two cases (Fig. 1).

Figure 4(b) shows the calculated results for peak current J_p, valley current J_v, and current peak-to-valley ratio (PVR) for GaAs/$Ga_{1-x}Al_xAs$ electron RTS's. The temperature variations of E_F, m_e^*, and μ_w have been included. In such RTS's, E_{Fn}^0 is often high, especially when the well width is small, and this large E_{Fn}^0 will affect the temperature properties of transport. When E_{Fn}^0 is large (thick spacer or narrow well), the peak current decreases and the valley current increases slowly with temperature. As discussed above, $g(E)$ depends on temperature and E_{Fn}, which, in turn, drops with temperature. With increasing temperature, the rise of $g(E)$ directly caused by increasing temperature [when E_F is a large constant (Fig. 1)] could be less than the decrease of $g(E)$ due to the drop of E_{Fn} with temperature [Eqs. (4) and (5)]. At the same time the transmission peak decreases due to μ_w decreasing with temperature [Eq. (6) and Fig. 2(b)]. The joint effects of these variations give rise to the decreasing temperature dependence of the peak current. These are just the typical experimental results for III-V electron RTS's with narrow wells ($\sim$40 Å) and thick spacers ($>$100 Å).[3,4] The above analyses reveal the physical origin of those experimental results. When E_{Fn}^0 is small (thin spacer and wide well), the peak current increases slowly with temperature and the valley current increases faster, since for smaller E_F the increase of $g(E)$ is faster (Fig. 1). This is consistent with experiments on InAs/AlSb DBRT's with wide wells (65 Å) and thin spacers (50 Å) (Ref. 6) and on light-hole resonant tunneling (with small E_{Fn}^0) in SiGe/Si DBRTS's.[5] For both cases, the decrease of the peak-to-valley ratio with temperature is due to the much faster increase of the valley current than that of the peak current.[12] It is obvious from Fig. 1 that the rise of $g(E)$ with temperature in the higher-energy range (which gives the main contribution to valley current, especially in the high-temperature region) is larger.

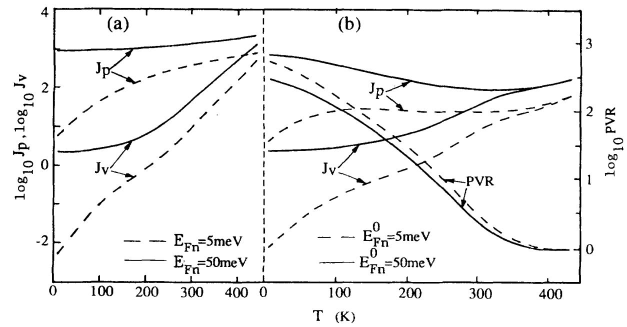

FIG. 4. The J_p J_v, and the PVR vs T in a RTS with parameters as in Fig. 3(a). The calculations were made using (a) constant E_F, μ, and m^*, and (b) temperature-dependent E_F, μ, and m^*.

IV. CONCLUSION

Analyses of the two factors determining resonant tunneling, i.e., the 1D CEDF $g(E)$, and the transmission, and calculations of the transport characteristics, show that the criterion of resonance is very different from the commonly used description based on the 3D CEDF. The subband energy at resonance E_{np} can be much lower or higher than E_F, depending on the RTS parameters. Resonant-tunneling transport calculations with constant E_F, μ, and m^* cannot give the decrease of peak current with temperature, which is often observed in experiments. In fact, the changes of these parameters with temperature and the E_F position *per se* are the main factors that influence the resonant-tunneling transport and its temperature dependence. By taking these factors into account, we have shown that it is possible to explain coherently the experimental results, e.g., the peak current decreases in most cases, while in some cases it increases with temperature.

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