# Origin of the Enhancement of Negative Differential Resistance at Low Temperatures in Double-Barrier Resonant Tunneling Structures

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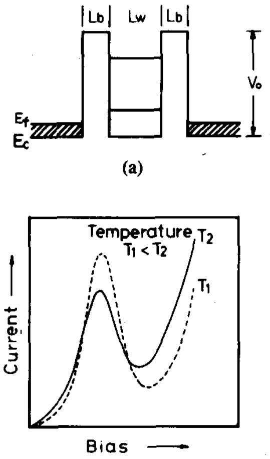
*Abstract*—**An explanation of the increased peak-to-valley (PTV) current ratio for double-barrier resonant tunneling structures (DBRTS's) operated at low temperatures is proposed. We found that this phenomenon is an inherent property of DBRTS's, not caused by the suppression of thermionic current over barriers. The energy distributions of electrons at different temperatures result in the variations of peak and valley currents.**

DOUBLE-BARRIER resonant tunneling structures (DBRTS's), demonstrated first by Chang *et al.* in 1974 [1], have attracted much attention recently. The structures can produce negative differential resistances (NDR's) and thus provide a wide variety of applications such as microwave oscillators [2], [3], frequency multipliers [4], and multivalued logics [5], [6]. Structures grown by molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) have been reported with large peak-to-valley (PTV) current ratios even at room temperature [7]–[9]. It has been shown that the NDR characteristics are more pronounced at low temperatures [7]–[18], but the reason is not very clear yet. The thermionic current over barriers [10] and the scattering effects [17] have been considered to explain this phenomenon. In this paper, a different approach which utilizes different electron distributions at different temperatures is used to explain this phenomenon. It is found that this temperature dependence is essentially an inherent behavior of DBRTS's. The contributions from thermionic current and scattering effects are only secondary.



(a)

(b)

Fig. 1. (a) Schematic energy band diagram of a typical DBRTS. (b) Typical current–voltage characteristics at different temperatures.

Fig. 1(a) shows a typical DBRTS. The device has a well width of $L_w$, symmetrical double barriers each with width $L_b$, a barrier height $V_0$, and a Fermi level $E_f$ above the conduction-band edge. The typical current-voltage characteristics at different temperatures are shown in Fig. 1(b). Only one bias polarity is presented and the scale is not indicated. When the temperature is reduced from $T_2$ to $T_1$, the peak current increases while the valley current decreases, giving rise to a larger PTV ratio. This trend has appeared in almost all of the DBRTS's. If the increase in PTV ratio at low temperatures is due to the decrease of leakage current because of the suppression of thermionic emission current over the potential barriers, the peak current should not increase [7], [8], [17], particularly in the low-temperature range of 77 to 4 K. So, there must be something other than thermionic emission to push the peak current up and pull the valley current down when the device is cooled.

Following Tsu and Esaki [19], we have calculated the $I$-$V$ characteristics of resonant tunneling devices to show the temperature dependence of PTV ratio and peak/valley currents for a set of structure parameters. In the calculation, the position of Fermi level is taken as fixed and the band-bending is not considered. For simplicity, a WKB approximation is used to estimate the transmission coefficients. The temperature dependence of the $I$-$V$ characteristics is accounted for by considering different electron distributions at different temperatures. Fig. 2 shows the calculated results. We can see that when the temperature is reduced, the peak current increases while the valley current decreases, therefore increasing the PTV ratio. The thermionic current is not included in the calculation and hence its contribution to this temperature

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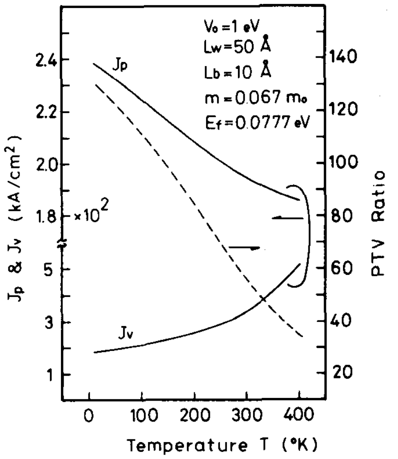

Fig. 3 Calculated temperature dependences of peak/valley currents and PTV ratio for the set of structure parameters shown in the insert.

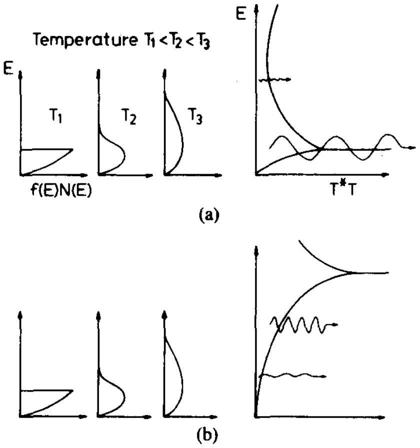

Fig. 3 Energy distributions of electrons at different temperatures when (a) the peak current and (b) the valley current occur. Transmission coefficents shown in right are not scaled.

dependence can be ruled out. The thermionic current is estimated to be about $2.5 \times 10^{-10}$ A/cm$^2$, which is negligible compared to the valley tunneling currents shown in this figure. Even if the band-bending effect is considered, the thermionic current is still insignificant since the band-bending simultaneously increases both the tunneling currents and the thermionic current by about the same amount. The transport mechanisms at different temperatures are qualitatively illustrated in Fig. 3.

Fig. 3(a) shows the condition when the peak current occurs. At temperature $T_1$, which is close to 0 K, almost all of the electrons are below the Fermi level. The electron densities per unit energy in this case are higher than those at temperatures above 0 K by a factor of the Fermi distribution function, which is temperature dependent. Therefore, if the peak transmissivity of the first resonant state occurs at an energy slightly below the quasi-Fermi level of the emitter, the tunneling current, which is proportional to the integral of the product of electron density and transmission coefficient, will be higher than those at higher temperatures. When the temperature rises to $T_2$, some of the electrons will move upward to higher energy states, causing a decrease in the amount of electrons having energies below $E_f$. Then, as the condition required for peak current is reached, some electrons will tunnel through the barriers with lower transmissivities corresponding to higher energy levels above $E_1$, resulting in a smaller current density. If the temperature increases even further, the energy distribution of electrons will extend further upward and the peak current decreases more. At high temperatures, although a small amount of electrons having high-energy states can resonantly tunnel through the second resonant state (if it exists), their contribution to the overall current is insignificant unless the well is very wide so that the second resonant state is very close to the first one. If this is the case, the peak current may have a different temperature dependence since the second resonant state can contribute a considerable current component at high temperatures. The explanation of the temperature dependence of the valley current is similar to that of the peak current and it is easy to realize as long as one inverts the above discussed effect, as shown in Fig. 3(b). We can see that, unlike its effect on the peak current, the second resonant state enhances the temperature dependence of the valley current.

Thermionic current over the barriers is not involved in our discussions and should not account for the reduction in PTV ratio at higher temperatures. To cite one example, [11] has shown a valley current of $10^3$ A/cm$^2$ at room temperature, obtained in a resonant-tunneling diode with AlAs barriers of 22.6 A. For this structure, the barrier height is assumed to be 1.036 eV (if the $\Gamma$ band and 0.65 fraction are taken) and the Fermi level is about 0.026 eV above the conduction-band edge of GaAs. We can estimate the thermionic current component. Given $m^* = 0.067 m_0$ and $T = 300$ K, we obtain a current density of $J_{th} = 8.4 \times 10^{-12}$ A/cm$^2$, which is negligible compared to the measured valley current although the thermionic current can increase with bias to some extent. Even if the $X$ band for AlAs and 0.65 fraction are taken, giving a barrier height of 0.484 eV, $J_{th}$ is only $1.5 \times 10^{-2}$ A/cm$^2$. If one checks several experimental results, it can be found that the PTV ratio at 4 K is larger than that at 77 K [20]–[22]. At such a low-temperature range, it is hard to see how the thermionic current plays an important part. So, we conclude that the enhancement of NDR at low temperatures is essentially an inherent character of the DBRTS. Of course, for the structures with barriers so low or/and with tunneling current so small that the thermionic current is large enough to dominate the valley current at high temperatures, the enhancement of NDR at low temperatures can be due to the suppression of thermionic current [20]. In general, one always uses barriers that are as high as possible to achieve a large PTV ratio, so the thermionic-current-dominated case is even more unlikely. The phonon-related scattering at low temperatures is reduced, so the PTV ratio increases due to peak current increase rather than valley current decrease. The scattering process alone cannot explain the experimental results satisfactorily.

In summary, we have presented an interpretation for the temperature dependence of the PTV ratio. We believe that this unique feature is an inherent characteristic of this type of device, regardless of other extrinsic factors. The reduced

**phonon scattering at low temperatures can additionally raise the PTV ratio mainly by increasing the peak current. The thermionic current, however, is insignificant because it is too small.**

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