Transmission zero engineering in lateral double-barrier resonant tunneling devices

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Transmission zero engineering in lateral double-barrier resonant tunneling devices is investigated. We show that, by inserting a resonant cavity in the quantum well region of a lateral double-barrier resonant tunneling structure and engineering the placement of transmission zero-pole pairs, the current peak-to-valley ratio of the device can be drastically improved at low temperature. An advantage of this structure also is that a lower peak voltage can be obtained compared to the corresponding lateral double-barrier resonant tunneling device. © *1996 American Institute of Physics.* [S0003-6951(96)01615-4]

A large number of investigations on double-barrier resonant tunneling (DBRT) devices have been reported; see, for example Refs. 1–7. It is believed that lateral resonant tunneling devices[4–7] possess some merits over their vertical counterparts.[1–3] For example, the artificially imposed barrier height and quantum well depth can be adjusted continuously, the shape and geometry of the gates can be defined with great flexibility, and a lateral device is more suitable for integrated circuit (IC) fabrication due to its planar structure. However, in both lateral and vertical double-barrier resonant tunneling devices, the current peak-to-valley ratio (PVR) is limited, even in the ballistic transport regime,[8] because their transmission minimum has a finite value.

Recent studies have shown that the electron's wave nature can give rise to new quantum waveguide devices on the nanometer scale.[9] Transistor action can be achieved in proposed stub-tuner devices.[10,11] Negative differential resistance region may also be obtained in the current-voltage characteristics of split-gate waveguides at low temperature.[12] In earlier studies, we found pronounced transmission properties of quantum waveguide systems with resonantly-coupled cavities.[13] Using a scattering matrix approach, we proved that transmission zeros exist on the real-energy axis in the above system. We found that each quasi-bound state in the resonant cavity leads to a zero-pole pair in the complex-energy plane which, in turn, leads to a strong modulation of the transmission probability.

In this letter, we apply this zero-transmission feature of the cavity to explore the possibility to maximize the current peak-to-valley ratio in two-dimensional lateral DBRT structures. Combining the transmission features of DBRT devices and of quantum waveguides with resonantly-coupled cavities, we insert a resonant cavity (stub here) in the quantum well region of a lateral DBRT structure (see Fig. 1). We show that the valley current in this device is reduced due to the zero-transmission feature of the stub. We also show that this device possesses a lower peak voltage compared to lateral DBRT devices, where peak voltage refers to the voltage at which the maximum current is reached.

For a lateral DBRT device, the first transmission peak, E_{pdbrt}, is determined by the energy of the first propagating mode of the channel, $E_{W_{ch}}=\hbar^2\pi^2/(2m^*W_{ch}^2)$, and the first quasi-bound state energy of the corresponding one-dimensional DBRT structure, $E_1=\hbar^2\pi^2/(2m^*W_s^2)$, i.e., $E_{pdbrt}=E_{W_{ch}}+E_1$. Due to the inserted stub, for the structure shown in Fig. 1, the first transmission peak, E_{pstub}, is determined by the bound state energy of the stub in the y direction, $E_L=\hbar^2\pi^2/(2m^*L^2)$, and E_1; approximately, $E_{pstub}=E_L+E_1$. Since L is always larger than W_{ch} (see Fig. 1), the position of the first transmission peak for the structure shown in Fig. 1 is always lower than that of the corresponding lateral DBRT device, i.e., $E_{pstub} < E_{pdbrt}$ (compare Fig. 2).

In order to utilize the resonant nature of the first transmission peak and transmission zero for the structure in Fig. 1, the peak energy must be higher than the energy of the first propagating mode of the channel, i.e., $E_{pstub} > E_{W_{ch}}$. Therefore, the corresponding design criterion for this device is that the dimension parameters, W_s, W_{ch}, and L, should satisfy $(L^{-2}+W_s^{-2}) > W_{ch}^{-2}$. We can achieve this condition by appropriately engineering the system dimensions.

In resonant tunneling devices, the peak and valley currents are determined by the values of the transmission probability at the maxima and minima, respectively. Since the transmission minimum is zero for the structure shown in Fig. 1 due to the inserted stub (see Fig. 2), its valley current is

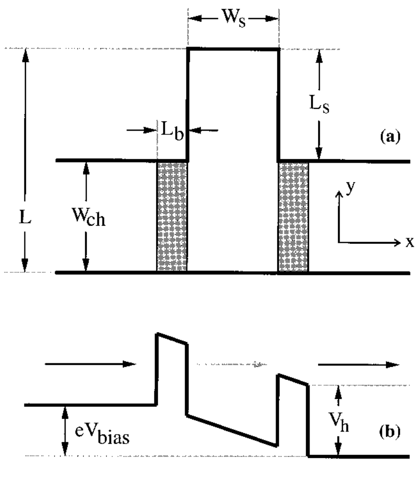

FIG. 1. (a) Schematic drawing of a quasi-one-dimensional lateral DBRT structure with an inserted stub. The shaded areas represent the potential barriers. (b) The device potential profile with an applied bias V_{bias}.

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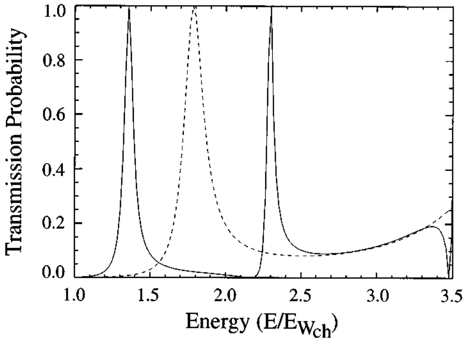

FIG. 2. Transmission probabilities of the new device (solid line) shown in Fig. 1 and the corresponding lateral DBRT device (dashed line).

reduced compared to the lateral DBRT devices. Furthermore, note that since $E_{pstub} < E_{pdbrt}$ and the position of E_{pstub} can be engineered, a lower peak voltage can be obtained for the new device.

We numerically modeled two-dimensional lateral DBRT with an inserted stub. Using the finite element method, we first solve the two-dimensional effective-mass Schrödinger equation in order to find the transmission probability $T(E,V)$ as a function of energy at different biases. We then calculate the current-voltage characteristics by

$$I(V)=\frac{2e}{h}\int_0^\infty [f(E)-f(E+eV)]T(E,V)dE, \qquad (1)$$

where $f(E)$ is the Fermi-Dirac distribution function. We choose a Fermi energy of $E_f=5$ meV in our calculation, which corresponds to a carrier density of 5.96×10^5 (1/cm).

We use an example to illustrate our analysis. We choose the following set of parameters for the structure shown in Fig. 1(a): $L=20.0$ nm, $W_{ch}=10.0$ nm, $L_b=1.5$ nm, $W_s=8.0$ nm, and $V_h=0.3$ eV. In Fig. 2, we show the transmission probabilities of this structure (solid line) and the corresponding lateral DBRT structure (dashed line) at zero bias. We have used the energy of the first propagating mode of the channel, $E_{W_{ch}}=\hbar^2\pi^2/(2m^*W_{ch}^2) = 56.1$ meV ($m^*=0.067m_0$), as the unit of the energy. Note that transmission zeros exist in the new structure.

For this particular set of device parameters, it happens that the DBRT transmission peak (dashed line) lies just about midway between the two peaks of the new device (solid line). If we were to increase the stub length L and keep the channel width W_{ch} unchanged, then the two peaks of the solid line will move toward lower energies, resulting in lower current-peak voltages.

Figure 3 shows the current-voltage characteristics of the above structure at several temperatures from $T=0$ to $T=100$ K (solid lines). The results of the corresponding lateral DBRT device are also shown (dashed lines). It can be seen that the PVR of the new device (PVR = 1457, 148.66, 49.60, 26.21, 15.93, 10.40) is improved over the corresponding lateral DBRT device (PVR = 18.56, 15.95, 13.04, 10.80, 9.10, 7.76) at the various temperatures ($T=0$, 20, 40, 60, 80, 100 K). Especially at low temperatures, the ratio increases substantially because of the near-zero valley current. Also, this enhancement of the PVR does not sensitively depend upon the height of the tunneling barriers since the energies of the DBRT transmission peaks are a weak function of the barrier height.

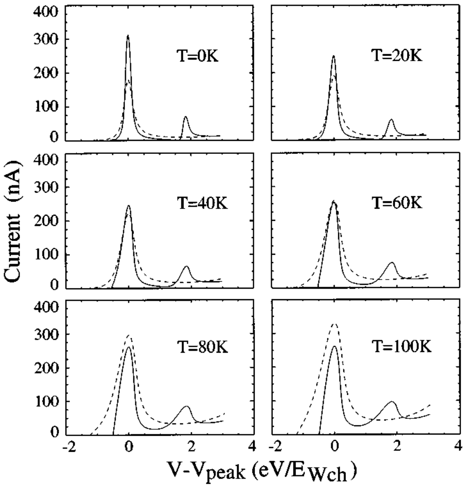

FIG. 3. Current-Voltage characteristics of the new device (solid line) and the corresponding lateral DBRT device (dashed line) at various temperatures.

The second current peak in Fig. 3 stems from the second transmission peak in Fig. 2, which is related to the second quasi-bound state in the stub.[13] At elevated temperatures, this transmission peak leads to an increase in the valley current and a corresponding decrease in the PVR. In order to reduce the contribution of this additional transmission peak to the valley current, it is required that the first and the second transmission peaks in Fig. 2 be well separated. This can be achieved by using smaller device dimensions since the energy difference between the first and the second transmission peaks increases with a reduction in size. With today's fabrication technology where the lithographic resolution approaches 10 nm, an experimental realization of our device appears to be feasible at low temperatures.

Note that in Fig. 3 the current is plotted as a function of the voltage difference $V-V_{peak}$, where V_{peak} is the peak voltage. The actual value of V_{peak} is the voltage at which the I-V curve intersects the $V-V_{peak}$ axis (zero current). From these figures, it can also be seen that lower peak voltages are obtained in the new device structure.

In DBRT devices, a lower peak voltage is obtained when the well width is large $[E_1=\hbar^2\pi^2/(2m^*W_s^2)]$. But, this also leads to a lower PVR since E_1 and E_2 are closer in this case. Therefore, there is a conflict between the requirements of low peak voltage and high PVR in DBRT device design. On the other hand, by inserting a resonant cavity in the quantum well region of a DBRT structure, both higher current peak-to-valley ratio and lower peak voltage may be achieved at the same time.

In our treatment here, we have used hard-wall boundary condition for simplicity. In real device design, a parabolic potential may be more appropriate for the channel and stub walls.[14] However, we expect the main conclusions to remain unaffected by the detailed choice of the confining potential.[15]

In summary, an approach for improving the PVR of lateral DBRT devices is investigated. Through engineering the

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zero-transmission feature of resonantly-coupled lateral waveguides, we find that the valley current of the proposed device structure may be drastically reduced compared to the lateral DBRT device. As a result, the current peak-to-valley ratio is increased. A lower peak voltage is also achieved in the new device structure. Both merits should offer better device performance.

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