Coherent-electron intrinsic multistability in a double-barrier tunneling diode

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Recently, a new mechanism leading to electrical multistability in coherent-electron tunneling devices was proposed. The reflection of coherent electrons at a barrier leads to the formation of resonant states in a quantum well in front of the barrier, and the resulting strongly modulated local density of states allows for multiple stable solutions of the Poisson equation to exist at fixed bias. These solutions are characterized by different resonant states being pinned close to the conduction-band edge, with each solution having its own unique tunneling characteristics. Here we show how these multiple-branch $I(V)$ characteristics can be engineered. This approach may open up new possibilities for high-speed functional devices.

Since Tsu and Esaki first proposed the resonant tunneling diode (RTD) in 1974,[1] growth techniques for heterostructure materials have been continuously improved, making it now possible to study the effect of electronic phase coherence on the transport properties of nanostructures. A RTD consists of at least one quantum well matched between two barriers and exhibits a strong negative differential resistance (NDR) in the $I(V)$ characteristic at a bias where either a filled quantum-well state drops below the conduction-band edge on the emitter side, or in the case of multiple wells, where two quasibound states in different quantum wells align. In either case the interference of coherent-electron wave functions is at the very heart of the NDR.[2] A few years later it was found that a charge buildup in the quasibound states can affect the $I(V)$ characteristic in a regime where the electrons tunnel sequentially from one quantum well to the next at *finite* bias.[3] In this case a linear charging/current relation leads to a characteristic intrinsic bistability with an associated hysteresis in the $I(V)$ curve.[4] Very recently, experimental data were reported on a room-temperature multistability with four distinct stable operating states occurring in a selectively doped two-terminal quantum tunneling device.[5] The fact that this device shows *zero-bias multistability* indicates that it cannot be explained along the lines of the sequential-tunneling bistability. Indeed, our recent analysis of a generic quantum-well/single-barrier structure in the coherent-tunneling regime[6] made clear that such a multistability is due to an electrostatic *pinning effect* of the lowest occupied quasibound or virtually bound state of a quantum well close to the conduction-band edge. A potential application of this effect in ultralow-power memory devices was proposed in Ref. 5.

In this letter we will show that by replacing the single barrier considered in Ref. 6 with a multiple-barrier tunneling diode one can tailor the $I(V)$ characteristics of the various stable operating states in a wide range, thus achieving completely different functionalities when switching from one state to another. This should be very useful for designing highly integrated quantum-functional devices. As an example we will discuss a double-barrier tunneling diode where the quantum well accommodating the pinned virtually bound states is formed by the accumulation layer.

As a simple model of an accumulation layer consider a square well in front of a high barrier at $x=0$, as shown schematically in Fig. 1. When a coherent electron with wave vector k_1 impinges on the barrier it interferes with its reflected wave to give a standing wave of the form $A\sin(k_2x)$, where k_2 is the wave vector in the well region and A^2 is given by

$$A^2=\frac{k_1^2}{k_2^2\cos^2(k_2d)+k_1^2\sin^2(k_2d)}. \quad (1)$$

This squared amplitude has for $k_1 \ll k_2$ resonant maxima at $k_2d\approx\pi/2,\ 3\pi/2,\ 5\pi/2,...$, which are called *virtually bound states* as they have energies *above* the band edge in region I. Being proportional to A^2, the electron number N in the well is strongly peaked at these energies. Next we analyze the electrostatic stability of this system in the case of complete inversion, where the virtually bound states get charged from the left side, while the bound quantum-well states below the band edge of region I are empty. Such an inversion can be achieved when the scattering rate to the quantum-well states is much smaller than the inverse in-

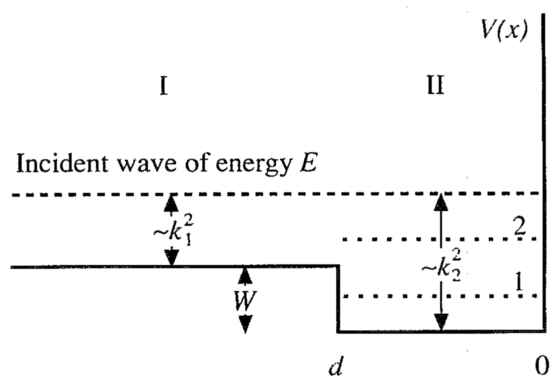

FIG. 1. Electrons impinging on a barrier at $x=0$ are reflected, leading to standing waves above the well in region II. The resulting electron number in well II is a strongly oscillating function of the wave vector k_2 with each resonance representing a virtually bound state. These states are unbound, as their energy E is higher than the potential in region I. Schematically indicated are a (quasi) bound (1) and a virtually bound state (2) in the quantum well.

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trinsic lifetime of these states due to tunneling through the right-hand barrier. In this case, when increasing the well depth W, the electron number N oscillates as the virtually bound states drop one by one below the conduction-band edge, thereby emptying towards the right-hand contact. The point is that *electrostatically stable* solutions of the Poisson equation must satisfy $dN/dW>0$, i.e., that the electron number *increases* with well depth. This is simply the condition that any change in the self-consistent potential must lead to a proper counteracting change in the electron density. It turns out that this increase is largest for a virtually bound state located just above the conduction-band edge in region I. This is the pinning effect: A stable solution to the Poisson equation is characterized by a filled virtually bound state (or quasibound state) pinned close to the conduction-band edge. In general, because of the oscillations in electron number, many solutions to the coupled set of Schrödinger and Poisson equations will exist. They differ in the quantum number of the pinned state or, in other words, in the number of bound states found in the quantum well. The stability of these solutions depends on how large dN/dW is, and it is clear from this discussion that for this multistability to occur in the first place, a sufficient coherence of the electron wave function is vital.

So far we have not considered in detail the structure of the right-hand barrier in Fig. 1. The crucial point for the multistable operation of the RTD is the fact that the effective height of this barrier is different for the various self-consistent solutions of the Poisson equation. As a result, the multiple stable operating states of the diode differ in the current they can carry. The simplest approach to engineer the tunneling-current characteristics of these states is to replace the single barrier on the collector side in Fig. 1 by a double barrier. For our numerical simulation we have chosen a double-barrier diode consisting of 200 Å n^+-GaAs (1×10^{18} cm^{-3}), 60 Å i-GaAs, 40 Å i-$Al_{0.33}Ga_{0.67}As$, 50 Å i-GaAs, 40 Å $Al_{0.33}Ga_{0.67}As$, 60 Å i-GaAs, 200 Å n^+-GaAs. As in Ref. 6, we calculated the electronic scattering states by using a standard transfer-matrix method[1,7] together with a Poisson-equation solver, and we evaluated the electron density quantum mechanically from the integral over probability times distribution function, $n(x)=\Sigma_k|\psi_k(x)|^2 f_k$, with the boundary condition of charge neutrality at the contacts. The tunneling current was evaluated with the Tsu–Esaki formula

$$\mathbf{J}=\frac{2e}{(2\pi)^3}\int d\mathbf{k}\,\mathbf{v}(\mathbf{k})\,|T(E,V)|^2[f_{FD}(E)-f_{FD}(E+eV)]. \qquad (2)$$

In our simulation we found *five* different stable operating states of the RTD, labeled I–V. Their $I(V)$ characteristics at $T=4.2$ K are shown in Fig. 2. Branch I starting at zero bias has been extensively discussed in literature on ballistic tunneling in RTDs. It exhibits a negative differential resistance at about 237 mV caused by the ground state in the double-barrier well dropping below the conduction-band edge on the emitter side. A similar resonance is seen in branch V at 450 mV. At certain biases switching occurs between the various branches, resulting in a complicated multistep hysteresis with many different possible closed loops when ramping the bias. For example, one possible hysteresis is given by the sequence I→IV→V→IV→III→II→I. To check our pinning-effect model of the multiple operating states of this RTD we have plotted in Fig. 3 typical self-consistent band profiles of all five current branches, including the positions of quasi-bound and virtually bound states. These data confirm that in all branches the respective lowest filled virtually bound state in the accumulation layer is pinned to the conduction-band edge. The branches differ in the quantum number of this state. In branch I the ground state of the accumulation layer is pinned, in branch II the first excited state, and so on.

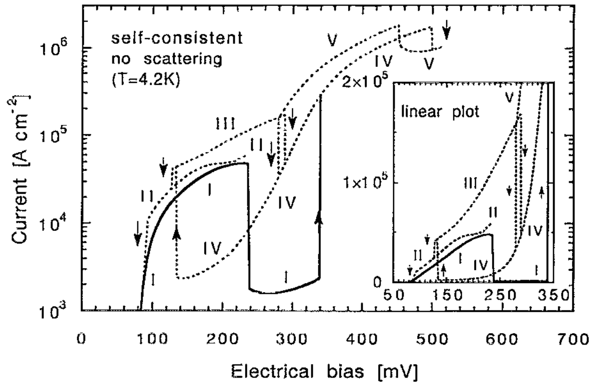

FIG. 2. Self-consistently calculated $I(V)$ characteristic of a coherent-electron double-barrier diode at $T=4.2$ K. In total, five current branches interconnected in a complicated multistep hysteresis structure can be distinguished, which correspond to five different virtually bound states pinned in the accumulation layer (see Fig. 3). Within each branch the operating point can be reversibly moved up and down by changing the bias, but switching between branches (indicated as vertical arrows) is irreversible. At zero bias the diode is always on branch I (solid line). When increasing the bias, the diode switches to branch IV at 340 mV and from that branch the diode can either switch to branch V if the bias is further increased, or to branch III in case the bias is lowered. The inset is a linear plot.

The $I(V)$ characteristics of this double-barrier diode are much more complicated than those of Ref. 6 for a single-barrier diode. This is a consequence of the operating states providing very different effective barrier heights and resonance conditions for tunneling electrons, resulting in a huge difference in the tunneling current. Changing the parameters of the barrier structure on the collector side of such a device will be a key method in engineering the $I(V)$ characteristics. In this way one can realize, within a single device and at a given bias, negative as well as positive differential-resistance characteristics.

In view of the potential applications, the stability of the multiple operating states is extremely important. The arrows in Fig. 2 indicate the bias values at which switching between branches takes place when the electrostatic pinning force breaks down. On the low-bias side of a branch such a breakdown occurs when the potential energy of the pinned virtually bound state becomes too high to assure

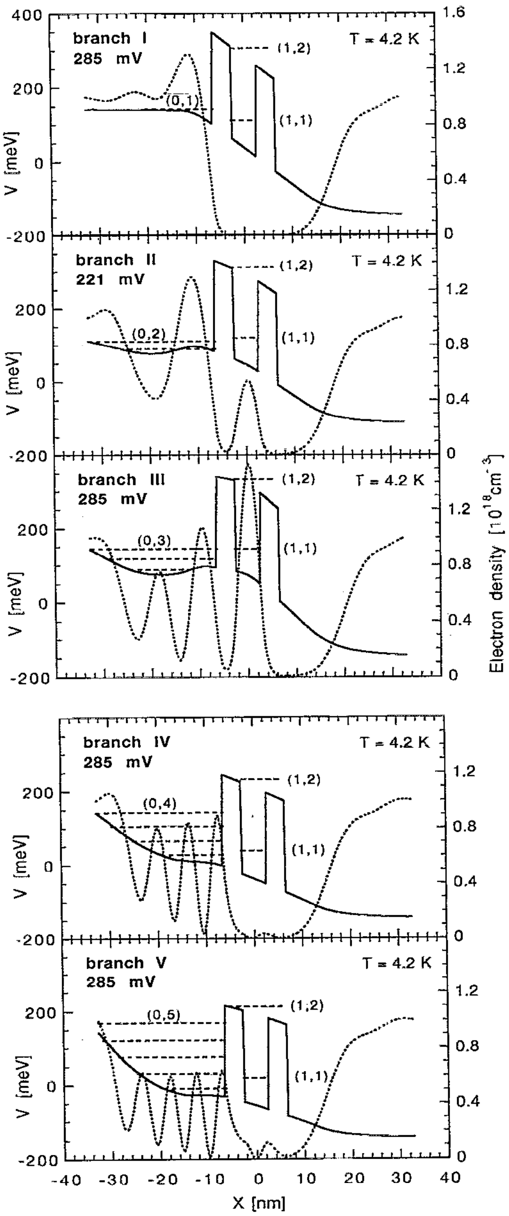

FIG. 3. Self-consistent potential profiles (solid lines) and electron densities (dotted lines) at a bias of 285 mV (221 mV for branch II) for the five current branches shown in Fig. 2. They differ in the number of bound states found in the accumulation layer. In branch n, n-1 states are bound and the nth state is a virtually bound state pinned closely to the conduction-band edge at the emitter side. The number of its nodes is mirrored in the electron density.

proper pinning (see branch V), whereas on the high-bias side it is triggered by the pinned virtually bound state dropping below the conduction-band edge (see branch III), so for optimal stability the device should work in the middle of a branch. Another degrading effect is the scattering to quasibound states in the accumulation layer, as this leads to an additional charge buildup in this layer which reduces the impact the charge accumulation in the pinned state can have. This problem can be solved by making the barriers transparent enough to ensure a proper draining of the quasibound states towards the collector contact. However, this problem will be more difficult to tackle for zero-bias devices as proposed in Ref. 5, as in equilibrium no such drainage is possible. Nevertheless, room-temperature operation of a multistable zero-bias device has already been successfully demonstrated over a period of a few minutes.[5]

Finally we note that in contrast to Ref. 5 we found only one stable operating state in the low-bias range. This is simply because in our structure some minimal bias is necessary to create a quantum well in the accumulation layer. With a built-in quantum well, multistability will occur at lower or even zero bias. The advantage of using virtually bound states instead of quasibound states for the pinning mechanism is their much shorter lifetime, which results in an improved switching performance.

In conclusion, we have studied a new kind of electrical multistability occurring in coherent-electron tunneling diodes. The underlying physical principle is very simple and general: The charge buildup in quasibound and virtually bound states of a quantum well/tunneling barrier structure has a tremendous impact on the self-consistent potential profile solving the Poisson equation. This highly nonlinear coupling between Schrödinger and Poisson equations leads to multiple solutions for the potential profile at fixed external bias. The stability of these solutions is due to the lowest filled resonant state being electrostatically pinned close to the conduction-band edge. This effect, which in principle can persist even up to room temperature, has many interesting possible applications, such as, e.g., ultralow-power memories or multivalued logical devices. In the present study we have numerically simulated a collector double-barrier tunneling diode where at high bias the accumulation layer can accommodate a number of quasibound and virtually bound states. As many as five different stable operating states were found corresponding to the different pinned resonant states. Moreover, we have shown that using a double-barrier structure is superior to a single barrier as it allows for the $I(V)$ characteristics of the different operating states to be engineered over a wide range, from positive to negative differential resistances. Thus the functional operations of many different devices may be incorporated within a single unit.

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