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Multistable Charge Build-Up and a New Switching Principle in Coherent-Electron Tunneling Devices

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A new mechanism leading to multiple stable operating states in coherent-electron tunneling devices is proposed and numerically verified in a model system. This mechanism utilizes the charge accumulation in virtually bound and quasi-bound states in a quantum-well/barrier structure. The electrostatic energy associated with these states causes the lowest occupied of them to be pinned to the conduction-band edge. For fixed bias, more than one solution to the Poisson equation is found, with each solution being uniquely determined by the quantum number of the pinned state. These different solutions show up as different current branches in the $I(V)$ characteristic of a tunneling diode. Switching between them — for example by using lateral gates — should be very fast, as virtually bound states have a much shorter life time than quasi-bound states.

KEYWORDS: tunneling, multistability, charge accumulation, virtually bound states, quasi-bound states, pinning

1. Introduction

Improving growth techniques for heterostructure semiconductor materials have made it possible to adopt a bandstructure-engineering approach to the design of new devices with outstanding features and entirely different underlying physical concepts, such as for instance the modulation doped field effect transistor (MODFET),[1] the velocity modulation transistor (VMT),[2] the hot electron transistor (HET),[3] the resonant tunneling diode (RTD),[4,5] or the tunnel base transistor (TBT).[6] High-speed memory devices and devices capable of performing increasingly complex logic functions constitute a major field of applications. A very interesting approach to this field is to utilize electrically multistable systems where each stable state represents a different logic value. An example for such a system is the heterostructure hot-electron diode (HHED) as proposed and first experimentally realized by Hess *et al.*[7,8] This device exhibits electrical bistability at fixed applied bias, as it can switch from a thermionic-current state to a tunneling-current state having an entirely different conduction-band profile and current magnitude as the former. In essence, the bistability arises from a locally varying nonlinear current-electric-field relationship, and is thus a nonequilibrium effect.[9] Very recently, experiments have been performed on a selectively doped two-terminal quantum tunneling device showing a *zero-bias multistability* at room temperature with four distinct stable operating states, which has potential applications in ultra-low-power memory devices.[10] In this structure the doping profile, a N^-–N^+–N^- spacer layer, was found to be crucial for the multistability to occur. The operating principle is entirely different from a HHED, as the spatial variation of the electron density in the four stable configurations indicates that a charging of the quasi-bound states in this structure is vital.

In this Letter we propose a general operating principle for such multistable systems based on the charging/decharging of virtually bound or quasi-bound electronic states in quantum-well/barrier structures.[11] The underlying physical principle is very simple: The potential profile in a quantum-mechanical device is a simultaneous self-consistent solution of the Schrödinger equation and the Poisson equation. These equations are coupled via the electronic charge distribution which has to be determined from the electronic wave function. In the quantum-mechanical regime, this wave function and hence the electronic charge distribution is very sensitive to the precise shape of the potential profile, resulting in a strongly nonlinear coupling of these equations. Therefore, for a suitable choice of parameters multiple stable solutions can be expected. It will be shown in this Letter that their main feature is a characteristic charging of virtually bound or quasi-bound electronic states, with a stability originating from an electrostatic pinning effect.

To maximize the impact of the electronic charge distribution on the solution of the Poisson equation, the doping concentration should be rather low in the region where the electronic wave function is coherent. This is in contrast to the findings of ref. 10, and we propose that the results of ref. 10 can be improved by utilizing a weak spatial modulation of the Al or In mole fraction to create shallow quantum wells instead of using selective doping. As the most simple example illustrating the principle idea, we will first discuss a shallow undoped well in front of a single barrier. Most of our analysis applies to virtually bound and quasi-bound quantum states equally well, but we will focus on the former as potentially they yield much faster devices.

2. A Simple Model

Our model consists of a square quantum well in front of an infinitely high barrier at $x=0$ as shown schematically in Fig. 1. We assume coherent electrons not suffering any scattering events. An electron of wave vector k_1 and energy E above the conduction-band edge impinging on the barrier is completely reflected, giving rise to a standing wave above the well of the general form $A \sin(k_2 x)$, where k_2 is the wave vector in the region of the well. With the matching conditions at $x=d$ we then have the system of equations

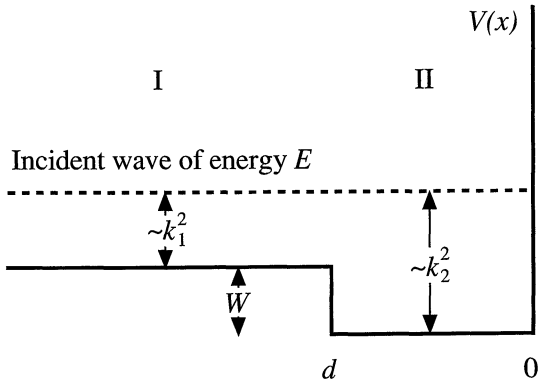

Fig. 1. Electrons impinging on a barrier at $x=0$ are reflected, leading to standing waves above the quantum well in region II. The resulting electron number in region II is a strongly oscillating function of the wave vector k_2 with each resonance representing a virtually bound state. These states are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

$$\begin{aligned} \sin(k_1 d+\delta) &= A \sin(k_2 d) \\ k_1 \cos(k_1 d+\delta) &= k_2 A \cos(k_2 d) \end{aligned} \tag{1}$$

which has the solution

$$A^2=\frac{k_1^2}{k_2^2\cos^2(k_2 d)+k_1^2\sin^2(k_2 d)}. \tag{2}$$

For $k_1 \ll k_2$ the squared amplitude A^2 has resonant maxima at $k_2 d \approx \pi/2,\ 3\pi/2,\ 5\pi/2, \cdots$. These resonances represent *virtually bound states* with energies above the band edge in region I. Integrating the probability function $|\psi(x)|^2$ from $x=0$ to $x=d$ gives the total electron number N in the well as

$$\begin{aligned} N &= \int_0^d \mathrm{d}x\, A^2 \sin^2(k_2 x) \\ &= \frac{A^2}{2}\left\{d-\frac{1}{2k_2}\sin(2k_2 d)\right\}. \end{aligned} \tag{3}$$

In Fig. 2 we have plotted the electron number $N(k_2)$ in — or rather above — the well for some wave vectors k_1 of the incoming electron. It should be noted that sweeping the wave vector k_2 means moving the bottom of the well, i.e., changing its depth W. As the bottom of the well moves, the energies of the virtually bound states shift correspondingly. When the energy $E \propto k_1^2$ of the incident electron coincides with the energy of such a virtually bound state, the electron number in the well is greatly enhanced. The smaller k_1 the narrower and more pronounced these resonances become. In conclusion, for fixed energy of the incoming electron, the electron number in the well exhibits resonances at certain well depths W.

However, for a *distribution* of incoming electrons having different energies the resonances in N will be smeared out. In Fig. 3 we have plotted for three different chemical potentials the electron number $N(W)$ integrated over a thermal distribution of incoming electrons. It is clearly seen though that as long as the chemical potential is less than the typical spacing between virtually bound states, the resonances in $N(W)$ remain well defined.

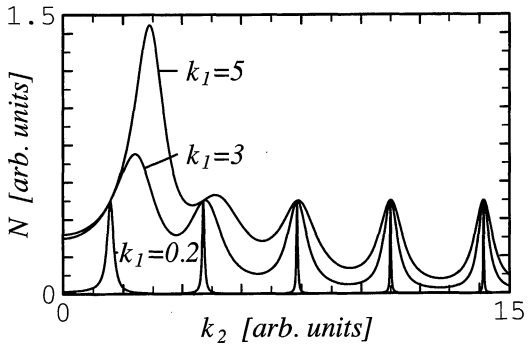

Fig. 2. Electron number N in well II as a function of the wave vector k_2 in this well for various energies $E \propto k_1^2$ of the incoming electrons. The resonances caused by the formation of virtually bound states are best defined for $k_1 \to 0$, i.e., for incoming electrons at the band edge. Below resonance, increasing k_2 means increasing N, while above resonance the opposite is true. Therefore, a stable solution to the Poisson equation can only be found for k_2 *just below* a resonance where $\mathrm{d}N/\mathrm{d}k_2 > 0$. It is separated from other solutions at other resonances by unstable regions with $\mathrm{d}N/\mathrm{d}k_2 < 0$. This is the pinning effect.

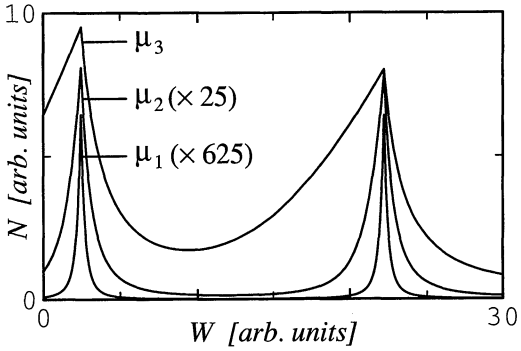

Fig. 3. Electron number N in well II as a function of well depth W for three different thermal distributions of incoming electrons with chemical potentials $\mu_1=0.01\Delta E$, $\mu_2=0.1\Delta E$, $\mu_3=\Delta E$, where $\Delta E \propto 2(\pi/d)^2$ is the typical separation of the virtually bound states.

These resonances in the electron number have an important consequence when self-consistently solving the Poisson equation. As a general rule in classical electrostatics, increasing the electron density at some point in space tends to raise the local self-consistent potential, as the electrons repulse each other, while decreasing the electron density means lowering this potential. This property assures the solution to the Poisson equation to be stable. In quantum mechanics, however, in the case of coherent electrons, this rule has to be modified. In Fig. 3 we see that as a function of the well depth W we have *stable* regions with $\mathrm{d}N/\mathrm{d}W > 0$ just below the resonances, and *unstable* regions with $\mathrm{d}N/\mathrm{d}W < 0$ above them. As a result, more than one stable solution to the Poisson equation is possible — one for each resonance. Each solution can be characterized by the quantum number of the virtually bound state causing the resonance. Just below resonance $\mathrm{d}N/\mathrm{d}W$ is largest and it is therefore this region where a self-con-

sistent solution to the Poisson equation is most likely to be found. In this case the virtually bound state is closely *pinned* to the conduction-band edge of region I in Fig. 1.

Such a multistability can be utilized in various ways. In this Letter we will consider the case of an adjacent tunneling barrier to be raised and lowered by the bottom of the well (which is then acting as an accumulation layer). The multistability will then show up as distinct current branches in the $I(V)$ characteristic of the tunneling diode.

3. Application to a Tunneling Diode

As an example to show how the pinning mechanism can be utilized we have investigated a model single-barrier system consisting of 90 Å n^+-GaAs [1×10^{18} cm^{-3}], 100 Å i-GaAs, 50 Å i-$Al_{0.25}Ga_{0.75}As$, 100 Å i-GaAs, 40 Å n^+-GaAs. The self-consistent electronic scattering states in this system were calculated by using the transfer-matrix method in conjunction with a 1D Poisson equation solver.[12] In each step the electron density was quantum mechanically determined according to $n(x)=\Sigma_\gamma|\psi_\gamma(x)|^2 f_\gamma$. The boundary condition on solving the Poisson equation is that the region close to the contacts has to be electrically neutral. The current was calculated by using the standard Tsu-Esaki formula

$$J=\frac{2e}{(2\pi)^3}\int \mathrm{d}\boldsymbol{k}\, \boldsymbol{v}(\boldsymbol{k})|T(E,V)|^2[f_{\mathrm{FD}}(E)-f_{\mathrm{FD}}(E+eV)]. \tag{4}$$

Numerical results for the $I(V)$ characteristic at $T=4.2$ K are shown in Fig. 4. They exhibit a rich structure of various current branches. The branch I covering the low-bias range is the one commonly investigated. The new features we are interested in in this Letter show up at some higher bias when a sudden switching to another branch occurs. In total, 4 different branches are successively switched through, numbered I to IV, which can uniquely be characterized by the quantum number of the virtually bound state in the accumulation layer.

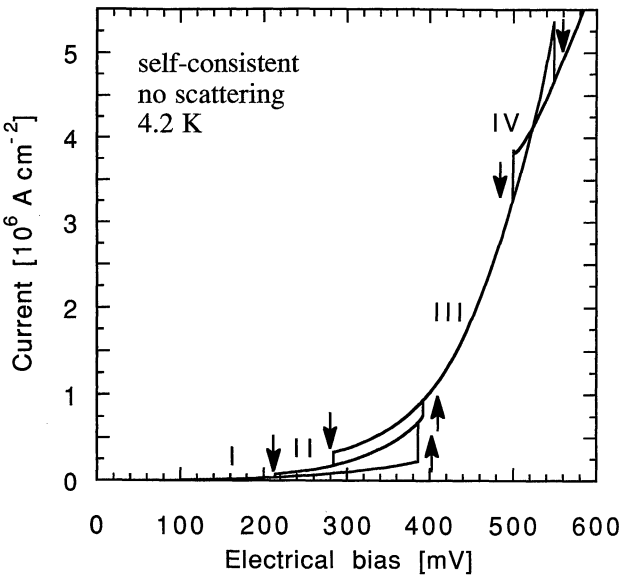

Fig. 4. $I(V)$ characteristic of a single-barrier diode at $T=4.2$ K, self-consistently calculated in the coherent-tunneling regime. In total, 4 current branches can be distinguished which correspond to 4 different virtually bound (respectively quasi-bound) states pinned in the accumulation layer (see Fig. 5). Switching between them is indicated by vertical arrows.

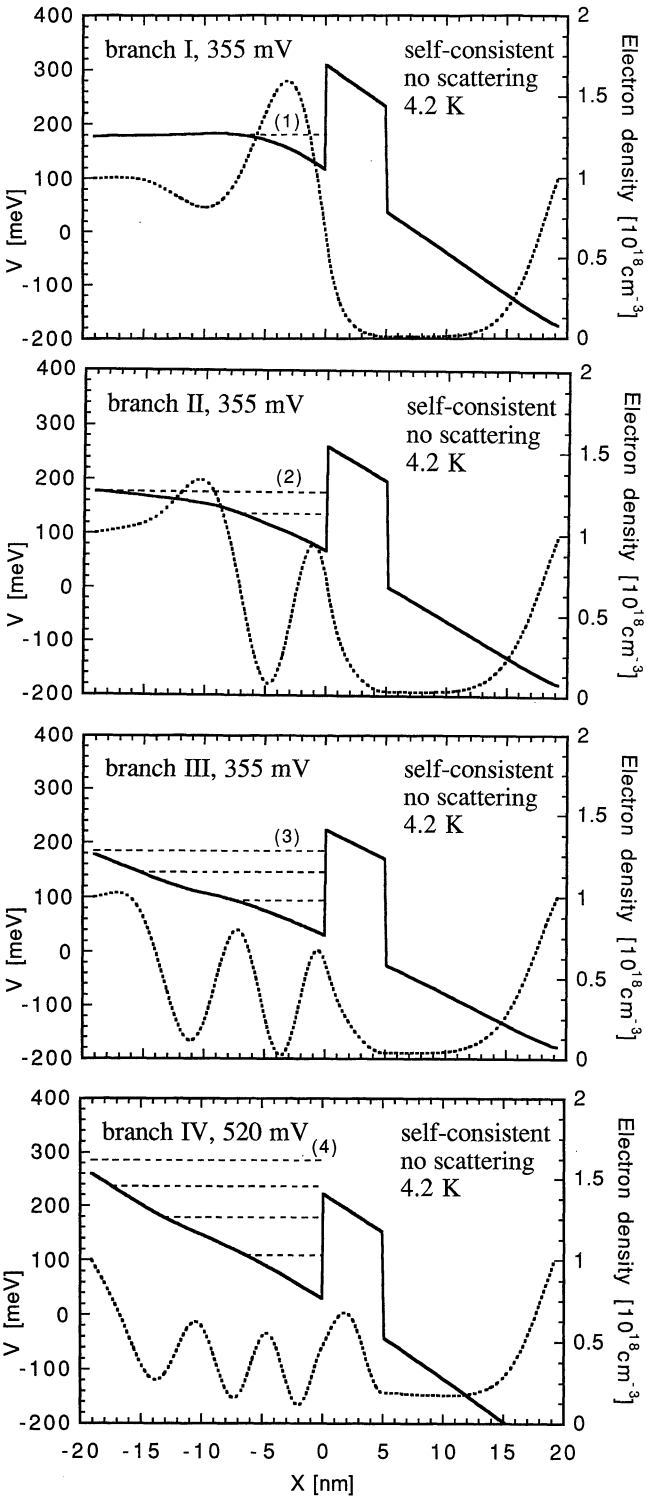

Fig. 5. Self-consistent potential profiles (solid lines) and electron densities (dotted lines) at a bias of 355 mV (520 mV for branch IV) for the 4 current branches shown in Fig. 4. They differ in the number of bound states found in the accumulation layer. In branch n, $n-1$ states are bound and the nth state is a virtually bound state (in case of branch I it is actually a quasi-bound state) pinned closely to the conduction-band edge at the emitter side. The number of its nodes is mirrored in the electron density.

tion layer pinned to the conduction-band edge. The self-consistent band profiles of Fig. 5 confirm that in branch I the ground state of the accumulation layer is pinned, in branch II the first excited state, and so on.[13] These solutions to the Poisson equation differ in current, as they have different effective barrier heights and resonant conditions. Switching between branches occurs when the electrostatic pinning force breaks down. On the low-bias side of a branch this happens when the energy of the pinned virtually bound state gets too high, while on the high-bias side the break down is caused by the *occupied* virtually bound state dropping below the conduction-band edge — thereby becoming an *empty* quasi-bound state. This behaviour exactly mirrors the regions of stability as found in Fig. 3.

Essential for this new mechanism to work is that the electron transport is predominantly coherent in the neighborhood of the barriers, as scattering to quasi-bound states in the accumulation layer will degrade the effect. Thus a basic requirement is that the scattering rate into these states must be much smaller than the inverse dwell time of these states. On the other hand, as seen in Fig. 3, the multistability is rather insensitive to how broad the distribution of incoming electrons is. In fact, we found multistable behaviour in this tunneling diode not only for a 4.2 K distribution but even for a 300 K distribution, in agreement with ref. 10.

In order to utilize such a multistability in devices, it is necessary to have some means of controlling the switching between the current branches without changing the bias. One way of doing this is to use a lateral gate selective to the plane of the accumulation layer. Another is to use light to generate additional carriers in this layer. In addition, the properties of the accumulation layer can be engineered by choosing other materials and/or dopings. Finally we note that the switching performance should be much better than that of conventional resonant tunneling diodes as the life time of not too strongly pinned virtually bound states is much shorter than the life times of quasi-bound states confined to wells.

4. Conclusions

In summary, a new mechanism leading to electrical multistability in coherent-electron devices has been proposed which is based on the charge build-up in virtually bound or quasi-bound electronic states and the corresponding charging energy. The potential profile employed to illustrate the general idea is very simple, it consists of a shallow nominally undoped quantum well in front of a tunneling barrier. At energies higher than the conduction-band edge on the emitter side the incoming electron wave interferes with its wave reflected at the barrier, thus causing resonances at certain energies above the quantum well — either virtually bound or quasi-bound states. The electrostatic energy associated with the high electron density of such a state has a strong impact on the self-consistent potential profile, in particular on the quantum-well depth, leading to a pinning of the lowest occupied virtually bound or quasi-bound state close to the conduction-band edge. In this way more than one self-consistent solution to the Poisson equation can exist. These solutions differ in the quantum number of the pinned virtually bound state. As an application of this mechanism we discussed the case of an accumulation layer in a single-barrier tunneling diode. Here the different self-consistent solutions to the Poisson equation lead to distinct current branches in the $I(V)$ characteristics. It is proposed to control switching between them by using lateral gates selective to the accumulation layer.

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12) The continuous energy spectrum was discretized with 10000 scattering states. After each step of the Poisson equation solver the energy mesh was refined to seek better resolution at the resonances. The chemical potentials in the contacts were determined by the condition of charge neutrality at the contacts.
13) The fact that the higher branches II to IV do not connect smoothly to the emitter contact is a consequence of our assumption made for simplicity that no phase-breaking events occur in this device. In reality, such events will happen at distances of the order of the phase breaking length away from the barriers, in which case the potentials will flatten out towards the contact region as usual.