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Indented barrier resonant tunneling rectifiers

M. Di Ventra[a)]
Institut de Physique Appliquée, Ecole Polytechnique Fédérale de Lausanne, PHB-Ecublens, CH-1015 Lausanne, Switzerland

G. Papp
Institute of Theoretical Physics, Attila Jozsef University of Szeged, H-6720 Szeged, Aradi vértanuk tere 1, Hungary

C. Coluzza
INFM Dip. di Fisica, Universitá di Roma ''La Sapienza,'' P. le A. Moro 2, 00185 Roma, Italy

A. Baldereschi
Institut de Physique Appliquée, Ecole Polytechnique Fédérale de Lausanne, PHB-Ecublens, CH-1015 Lausanne, Switzerland

P. A. Schulz
Instituto de Física ''Gleb Wataghin,'' C.P. 6165, UNICAMP, 13083-970 Campinas, S.P., Brazil

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This article concerns a novel negative-conductance device consisting of a series of N laterally indented barriers which exhibits resonant tunneling under one bias polarity and simple tunneling under the opposite one, thus acting as a rectifier. Electrons undergo resonant tunneling when the bias creates a band profile with N triangular wells which can each contain a resonant state. From 1 to N the addition of each indentation can be used to increase the current density and the rectification ratio, calculated at the current-peak bias at resonance, provided that at a given bias all the states in the triangular wells align each other with the emitter Fermi energy in order to form a resonance along the structure. © *1996 American Institute of Physics.* [S0021-8979(96)07019-3]

I. INTRODUCTION

Resonant tunneling through multi-barrier quantum structures is known since the pioneering work by Chang *et al.*[1] Nevertheless, only a decade later, improvement of the quality of the tunneling heterostructures led to envisage their potential application as electronic and optoelectronic devices.[2,3] Since then there has also been a major effort to understand the phenomenon from a theoretical point of view.[4–8]

One of the feasible applications of resonant tunneling structures is as a quantum well ultra-fast oscillator. In this context Sollner *et al.*[9] have demonstrated that operation of double-barrier quantum well diodes in an ac field can result in dc negative differential resistance (NDR) at small dc bias voltage. The explanation of this result was given by Liu and Coon,[10] based on the theory of resonant tunneling. Afterwards it was shown that two-step single barrier diodes (SI) may be used as rectifying devices,[11,12] opening up the possibility of observing NDR under an ac field in the absence of a dc voltage, due to their intrinsic asymmetry.[11] Moreover, the potential barriers which control rectification as well as the resonant mechanism are independent of the charge carrier distribution.

In the present work it is shown that the reverse-bias current density and the rectification ratio can be considerably enhanced using a sequence of N barriers.

[a)]Electronic mail: diventra@irrmasg11.epfl.ch

II. RESULTS AND DISCUSSION

The structure consists of a degenerately doped tunneling emitter, an N-indented single barrier, and a degenerately doped collector. For the sake of clarity, attention will be focused on SI, double-indented (DI), and triple-indented (TI) diodes. The total length of the active layer is kept nearly constant, in order not to change the positive-bias current. The unbiased conduction band profile for a TI single barrier is shown in Fig. 1. The unbiased conduction-band profile for SI and DI single barriers can be inferred assuming one and two indentations, respectively, in Fig. 1. With a reverse bias, the three steps become triangular wells, a quasi-bound state appears in each one, and resonant-tunneling current can flow through the structure when the three states match a state (near the Fermi level) in the emitter forming a single resonance of the structure [see Fig. 2(a)]. By applying forward bias, a very low current flows and the device acts as a rectifier [Fig. 2(b)]. The magnitude of this current essentially depends, in exponential form, on the thickness of the active layer. It can thus be easily controlled by changing the width of the barriers. In reverse bias condition, the existence of other quasi-bound states, in addition to the single quasi-bound state of the SI diode, has the effect of increasing the probability of transmission of an electron from the emitter to the collector, thereby enhancing the current density. N-indented diodes, with N>3, may show interesting finite superlattice properties, with qualitatively different confining effects on electrons and holes as a function of applied voltage polarity. Here, however, attention will be focused on the rectification enhancement with increasing N.

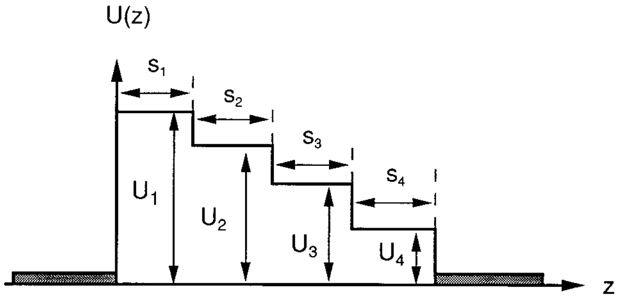

FIG. 1. Unbiased conduction band profile of a triple-indented diode.

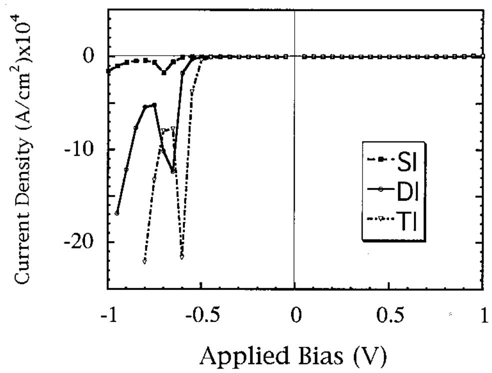

FIG. 3. The current density vs the applied voltage characteristics for the TI diode (dashed-dotted line), the DI diode (solid line), and the SI diode (dashed line).

The conduction band profile of Fig. 1 can be realized, for example, by N layers of AlGaAs with different Al concentration, which form the active layer between two n-doped GaAs contacts.

We modeled the current-voltage (J-V) characteristics of these AlGaAs/GaAs multistructures in the effective-mass approximation using the transfer matrix formalism,[13] consisting of solving the one-electron Shrödinger equation with scattering wave conditions, calculating the transmission coefficient and the particle flux, and finally averaging the latter over initial and final Fermi–Dirac distributions in order to obtain the current for each applied voltage. A detailed description of the calculations can be found elsewhere.[14] The inelastic processes as well as many-body effects which could be important for a detailed comparison between the real performances of the device and the theoretical predictions were neglected. The concern here is with the outlines of the transport properties of the structure; the above model has demonstrated its usefulness for this aim.[1]

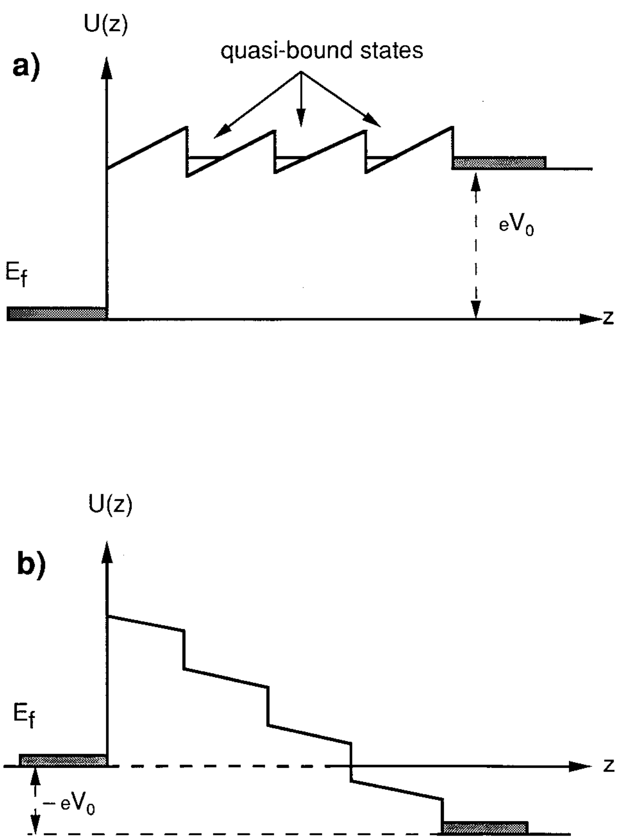

FIG. 2. Conduction band profile of the TI diode in (a) reverse bias case and (b) forward bias. V_0 is the external potential.

In Fig. 3, the J-V characteristics of a TI diode (dashed-dotted line), a DI diode (solid line), and a SI structure (dashed line) are shown. The materials parameters are chosen in order to keep the positive-bias current unchanged for the above three structures and this can be simply obtained choosing an equal total length of the active layer. The effective mass is expressed as $m^*(x)=(0.067+0.083x)m_0$, where m_0 is the free electron mass and x is the Al concentration of the barriers[15] (see Fig. 1 for the meaning of the symbols). For the SI diode, $U_1=0.45$ eV, $U_2=0.3$ eV, $S_1=30$ Å, and $S_2=60$ Å; for the DI diode $U_1=0.45$ eV, $U_2=0.3$ eV, $U_3=0.15$ eV, $S_1=30$ Å, $S_2=30$ Å, and $S_3=30$ Å, and for the TI diode $U_1=0.45$ eV, $U_2=0.35$ eV, $U_3=0.20$ eV, $U_4=0.10$, $S_1=25$ Å, $S_2=25$ Å, $S_3=25$ Å and $S_4=25$ Å. Offsets for the Γ profile up to 0.45 eV are used in order to minimize the $\Gamma-X$ coupling effects,[16] which, in any case, have only been clearly identified in AlAs single barrier devices[17] and should have no major influence on the rectification properties analyzed here. On the other hand, the complexity introduced by the X-like states may be interesting from a fundamental physical point of view, since the X minimum will also define a N-indented barrier with opposite polarity. The temperature is 77 K and the Fermi level of the degenerately doped emitter and the collector is positioned at 20 meV above the bottom of the conduction band (the zero of the energy scale).

The current density in reverse bias is much larger for the TI and DI diodes than the SI diode, and the TI diode shows a higher rectification ratio than the DI diode; the rectification ratios (defined as the ratio between the maximum negative-bias current and the symmetric positive-bias current) are ≈ 950 for the DI, ≈ 2500 for the TI, and ≈ 100 for the SI diode. The peak-to-valley ratios are instead practically the same, $\approx(3:1)$. Thus, the addition of an indentation to the SI diode increases the rectification ratio of about an order of magnitude. Another indentation further increases the rectification ratio by a factor of ≈ 2.5.

The N-indented barrier can be thought as a single triangular barrier in the forward direction. Therefore all the devices shown here show the same behavior for forward bias, since the length of two sides of the triangles are kept constant (the active layer of the device is nearly equal and the highest barrier step is the same for the three diodes). In the reverse bias situation, the effective barriers that define the triangular wells become smaller with an increase in the number of indentations. Therefore the resonances become wider with increasing N, resulting in two related effects: higher peak currents, but also higher off-resonant currents.[18] This behavior leads to a nearly constant peak-to-valley ratio, but increasing rectification with the number of indentations. It should be noted that there is no gain in the transmission probability if the quasi-bound states of each triangular well are not all lined up with the states near the Fermi energy. The rectification ratios depend, of course, on the material parameters of the structures and rectification is predicted for any structure containing at least one such element. It is expected to increase by putting in series several elements of this kind.[12]

III. CONCLUSION

In conclusion, novel structures which exhibit resonant tunneling under one bias and simple tunneling under the opposite one are proposed. These rectifiers are improved versions of the single-indented quantum structure previously proposed.[11] They consist of N indented barriers and the addition of each indentation (in the suitable way explained above) increases rectification. Since these quantum structures use tunneling as the conductivity mechanism, very fast delay times in their performances are expected. This could find application in high-speed electronics.

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