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Citation for published version (APA):
Racec, P. N., Stoica, T., Popescu, C., Lepsa, M. I., & Roer, van de, T. G. (1997). Physics of optimal resonant tunneling. *Physical Review B: Condensed Matter*, *56*(7), 3595-3597. https://doi.org/10.1103/PhysRevB.56.3595

DOI:
10.1103/PhysRevB.56.3595

Document status and date:
Published: 01/01/1997

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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PHYSICAL REVIEW B VOLUME 56, NUMBER 7 15 AUGUST 1997-I

Physics of optimal resonant tunneling

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(Received 26 July 1996; revised manuscript received 10 April 1997)

The optimal resonant tunneling, or the complete tunneling transparence of a biased double-barrier resonant-tunneling (DBRT) structure, is discussed. It is shown that its physics does not rest on the departure from the constant potential within the barriers and well, due to the applied electric field, but on the effective symmetry of the rectangular-barrier profile, which approximates the real potential profile for the corresponding applied bias. [S0163-1829(97)09331-4]

Ricco and Azbel[1] (RA) have been the first to outline the possibility of optimizing up to unity the transmission of a resonant-tunneling structure under field. They even quantitatively defined the corresponding necessary condition, which is that the two barriers should be functionally equal ($T_{\text{left}}=T_{\text{right}}$) at the resonance voltage. But the optimization procedure they outlined was cumbersome due to the matrix treatment they used, and they restricted the optimization range by considering that resonant tunneling no longer appears when the second barrier disappears due to bias.

Answering the need for a more rigorous treatment of the effect of the electric field, applied on the double-barrier resonant-tunneling (DBRT) structure, Allen and Richardson[2] (AR) have developed a matrix treatment based on Airy functions. They find that it is possible to produce asymmetric DBRT structures which, for sufficiently high applied biases, yield resonance transmission coefficients that are higher than those for symmetric structures. The question arises whether the possibility of such complete tunneling transparence of the DBRT structure is indeed a consequence of the field-induced nonconstant potential profile within barriers and well, appropriately described by the Airy functions treatment. We suggest in the following that the answer is no. In addition, AR did not elaborate on how they came across their optimal situations. They have just shown they exist, but they are not expected to result in a maximum in the I-V curve, as they correspond to energies rather far from the conduction band minimum (RA were among the first to clearly draw attention to such a requirement).

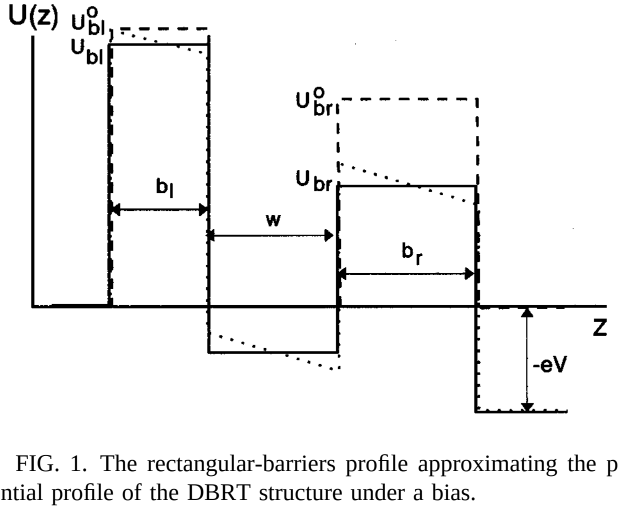

FIG. 1. The rectangular-barriers profile approximating the potential profile of the DBRT structure under a bias.

Rather successful modeling of the I-V curve of real DBRT structures was previously performed by van de Roer and co-workers[3,4] with a matrix formalism for rectangular-barrier structures which approximate the real structure at a given voltage bias. We will further use their formalism. The rectangular-barrier profile, or structure, approximating a certain DBRT structure under a certain bias V, is illustrated in Fig. 1. In terms of the tunneling probabilities of the left and right rectangular barriers, T_l, T_r, the resonant maximum transmission can be written as

$$T_{g,m}=\frac{T_l T_r}{[1-\sqrt{(1-T_l)(1-T_r)}]^2}\simeq\frac{4T_l/T_r}{(1+T_l/T_r)^2}, \quad \text{for } T_l, T_r<1 \tag{1}$$

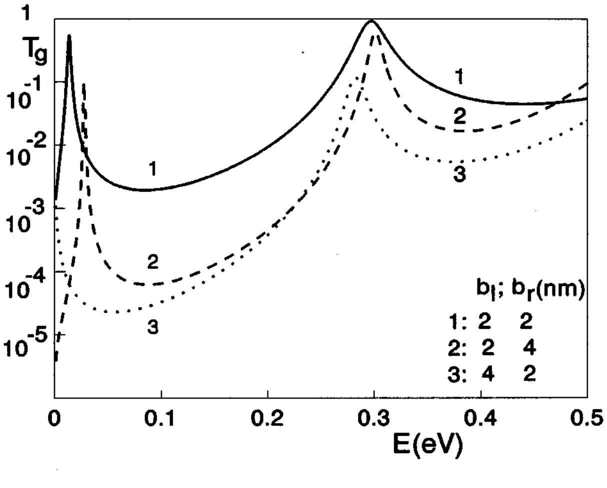

FIG. 2. Tunneling transmission in rectangular-barrier structures matching those in Fig. 3 (Ref. 4): $U^0_{bl}=U^0_{br}=0.5$ eV; $w=5$ nm, $V=0.16$ V; $m^*_l=m^*_w=m^*_r=0.067m_e$; $m^*_{bl}=m^*_{br}=0.1087m_e$; Curve 1, $b_l=b_r=2$ nm; Curve 2, $b_l=2$ nm, $b_r=4$ nm; Curve 3, $b_l=4$ nm, $b_r=2$ nm.

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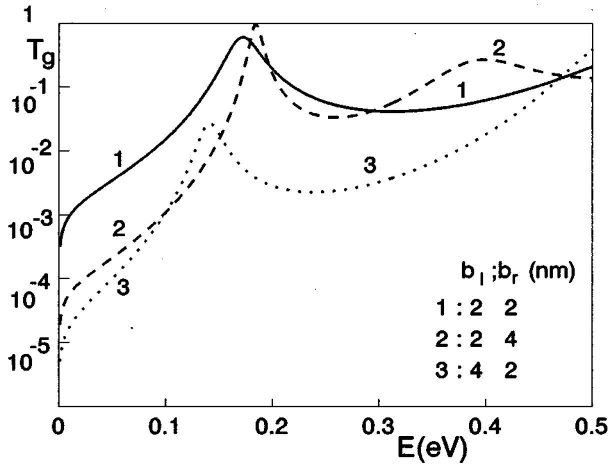

FIG. 3. Tunneling transmission in rectangular-barrier structures matching those in Fig. 4 (Ref. 4): $U_{bl}^0 = U_{br}^0 = 0.5$ eV; $w = 5$ nm, $V = 0.4$ V; $m_l^* = m_w^* = m_r^* = 0.067 m_e$; $m_{bl}^* = m_{br}^* = 0.1087 m_e$; Curve 1, $b_l = b_r = 2$ nm; Curve 2, $b_l = 2$ nm, $b_r = 4$ nm; Curve 3, $b_l = 4$ nm, $b_r = 2$ nm.

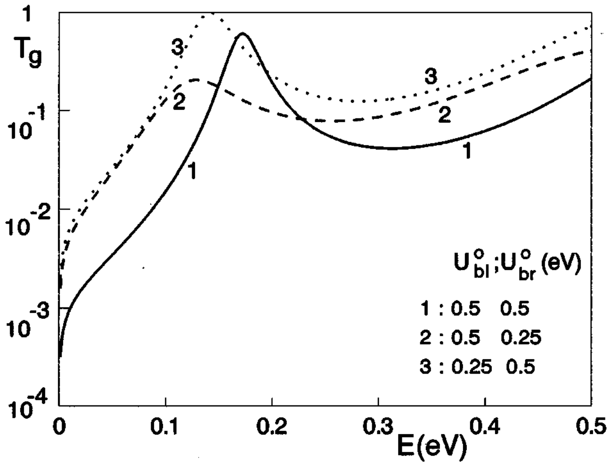

FIG. 4. Tunneling transmission in rectangular-barrier structures matching those in Fig. 5 (Ref. 4): $b_l = b_r = 2$ nm; $w = 5$ nm, $V = 0.4$ V; $m_l^* = m_w^* = m_r^* = 0.067 m_e$; $m_{bl}^* = m_{br}^* = 0.1087 m_e$; Curve 1, $U_{bl}^0 = U_{br}^0 = 0.5$ eV; Curve 2, $U_{bl}^0 = 0.5$ V, $U_{br}^0 = 0.25$ eV; Curve 3, $U_{bl}^0 = 0.25$ V, $U_{br}^0 = 0.5$ eV.

The problem is whether the physics for optimal resonance tunneling within a rectangular structure has any relevance for the physics of real DBRT structure under bias. In order to check this we have calculated the transmission probability for rectangular structures approximating all the structures calculated by Allen and Richardson with their Airy function procedure. The results are shown in Figs. 2, 3, and 4, and their pattern is strikingly similar to that in Figs. 3, 4, and 5 in Ref. 2 due to practical coincidence of the resonance energies, and even of the transmission peaks when close to unity, as can also be seen from Table I. The data in Table I show that the enhancement towards 1 and all the shifts in energy of the transmission peaks, of the biased DBRT structures discussed in Ref. 2, are fully quantitatively accounted for by the behavior of the approximating rectangular structures. In other words, at least within the bias range investigated in Ref. 2, for the physics of optimization of a DBRT structure up to complete transparence, the effect of the electric field within the barriers and well (departures from constant potential) appears to be insignificant. The field action appears to be only a global one, through its influence on the effective symmetry of the rectangular profile barrier, which approximates the real one for the corresponding applied bias. Thus, the physics behind the optimal transmissions $T_{g,m} \simeq 1$ obtained by AR is nothing else than the effective symmetry condition $T_l / T_r \simeq 1$, which is not a very restrictive one (the transmission gets above 0.9 when the above ratio is about 0.52). A last interesting thing shown by Table I is that the optimum transmission in Fig. 4 curve 2 (same curve in our Fig. 3) is obtained for an energy which is above the second barrier, which no longer acts as a tunneling barrier, but as a reflecting zone with resonances (as generally known). Such a possibility seem to have been missed by RA.

The results presented above suggest that the optimization of DBRT structures can be significantly eased if the use of approximating rectangular structures is combined with the more general concept which regards DBRT structures as composed of a tunneling barrier and a reflecting structure be-

TABLE I. Rectangular approximation versus the Airy function calculation.

DBRT	Values in Ref. 2		Approximating rectangular structure					
structure in Ref. 2, V	$T_{g,m}$	E_m, eV	$T_{g,m}$	E_m, eV	T_l	T_r	U_{bl}, eV	U_{br}, eV
Fig. 3, curve 1, 0.16 V	$\simeq 1$	$\simeq 0.30$	0.924	0.297	1.57×10^{-1}	2.59×10^{-1}	0.482	0.358
Fig. 3, curve 2, 0.16 V	$\simeq 0.37$	$\simeq 0.30$	0.625	0.301	1.58×10^{-1}	4.04×10^{-2}	0.485	0.369
Fig. 3, curve 3, 0.16 V	$\simeq 6.6 \times 10^{-3}$	$\simeq 0.28$	0.116	0.282	8.74×10^{-3}	2.47×10^{-1}	0.471	0.355
Fig. 4, curve 1, 0.40 V	$\simeq 0.43$	$\simeq 0.18$	0.610	0.172	9.76×10^{-2}	3.59×10^{-1}	0.456	0.144
Fig. 4, curve 2, 0.40 V	$\simeq 1$	$\simeq 0.20$	0.982	0.184	1.01×10^{-1}	1.30×10^{-1}	0.463	0.172
Fig. 4, curve 3, 0.40 V	$\simeq 2.3 \times 10^{-4}$	$\simeq 0.14$	2.67×10^{-2}	0.141	2.71×10^{-3}	3.30×10^{-1}	0.427	0.136
Fig. 5, curve 1, 0.40 V	$\simeq 0.43$	$\simeq 0.18$	0.610	0.172	9.76×10^{-2}	3.59×10^{-1}	0.456	0.144
Fig. 5, curve 2, 0.40 V	$\simeq 3.1 \times 10^{-2}$	$\simeq 0.14$	0.204	0.129	7.65×10^{-2}	7.65×10^{-1}	0.456	−0.106
Fig. 5, curve 3, 0.40 V	$\simeq 1$	$\simeq 0.15$	0.999	0.142	3.48×10^{-1}	3.30×10^{-1}	0.206	0.144

hind. Given a certain first barrier (in the rectangular approximation compatible with the bias at which tunneling transparence for the whole DBRT structure at a given energy is desired), a convenient rectangular well and second barrier can be added to it (also compatible with the bias), which ensure the requirements for the optimal resonant tunneling.

ACKNOWLEDGMENTS

One of the authors (M.L.) would like to thank the Electrical Energy Department of the Technical University of Eindhoven for support. Thanks are also due to the Humboldt Foundation for help with computing equipment.

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