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REFLECTION EFFECT OF LOCALIZED ABSORPTIVE POTENTIAL ON NON-RESONANT AND RESONANT TUNNELING

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ABSTRACT

The reflection due to absorptive potential $(-iV_i)$ for resonant and non-resonant tunneling has been considered. We show that the effect of reflection leads to a non-monotonic dependence of absorption on the strength V_i with a maximum absorption of typically 0.5. This has implications for the operation of resonant tunneling devices. General conceptual aspects of absorptive potentials are discussed.

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The transmission and reflection coefficients for an electron tunneling coherently through a double or multiple potential barrier show pronounced structure as the energy of the incident electron is tuned through the discrete quasibound eigenstates sustained by such a potential profile. These resonances are of course elementary consequences of quantum mechanical interference due to coherent multiple scattering. They have been studied extensively[1] in recent years in the context of double-barrier heterostructures with considerable attention to quantum devices based, for example, on their negative differential conductance at certain energies. These resonances are implicated fundamentally in the now well known phenomena of conductance fluctuations in disordered conductors, where they are identified as Azbel resonances. These electronic phenomena have obvious photonic counterparts though with some notable differences to be commented upon below.

More recently, attention has been focused on the effects of inelastic scattering on the otherwise coherent tunneling through potential barriers[2-7]. These inelastic processes are inherent to such structures as for example due to thermal phonons. The inelastic scattering introduces incoherence (dephasing) arising from the exchange of energy and requires a multichannel generalization of the usual treatment of tunneling. No such comprehensive treatment exists so far. This would be needed for a complete understanding of the cross-over from coherent to sequential tunneling.

Drastic simplification, however, results from the phenomenologically modelling of the incoherent effects by introducing an optical (non-hermitian imaginary) potential well known from nuclear physics. This corresponds to the absorption of probability current. We should note here that the term absorption in this context has been used in two senses that correspond to different physical situations. The first refers to the actual removal of the particle by a recombination process but leaving the surviving probability current coherent. The second corresponds to depletion of the spectral weight from the elastic channel, identifying the spectral weight lost in the inelastic channels as absorption. To be precise, if the spectral weight of the incident electron is $A(k,\omega) = \delta(\omega - E_k)$, the absorption would mean $A(k,\omega) \rightarrow \eta\delta(\omega - E_k) + A_{inc}(k,\omega)$ with $\int A_{inc}(k,\omega)\, d\omega = 1 - \eta = absorption$. We must point out however that a real inelastic scattering such as that due to phonon scattering would make $A(k,\omega)$ diffuse with no δ-function central peak. However, at finite energy resolution the central part of $A(k,\omega)$ may be treated as a δ-function of strength η riding a diffuse background of strength $1 - \eta$.

In this communication we propose to address the effect of possible mismatch caused by the absorptive potential $-iV_i$ that leads to non-monotonic dependence of absorption on the strength V_i. More specifically, we find that as V_i increases the absorption goes through a maximum and then falls off to zero. The reflection (transmission) coefficient, however, increases (decreases) monotonically. This reflecting aspect of the absorptive potential has so far been ignored in the treatment of resonant tunneling. This is hardly warranted. In point of fact for some examples quoted in the literature[4] the reflection turns out to be over 90% of the probability current, which would adversely affect the device performance. This behaviour of the absorption is counterintuitive and may be understood in terms of enhanced reflection due to potential mismatch. Absorption without reflection is *not* possible. This result holds both for resonant as well as non-resonant tunneling situations. Such phenomena and their interpretation seems to have been missed by workers in this field who have employed imaginary potentials to model absorption. This is presumably due to the fact that most authors have concentrated on resonance energy and used Breit-Wigner type approximations that miss this point. In order to make our point clear we will first consider the simple case of a purely absorptive delta-function potential $V(x) = -iV_0\delta(x)$.

The corresponding reflection $R(E)$, transmission $T(E)$ and absorption $\sigma(E)$ coefficients are:

$$
\begin{aligned}
R(E) &= \frac{V_0^2}{(\hbar^2 k/m + V_0)^2}\,,\\
T(E) &= \frac{(\hbar^2 k/m)^2}{(\hbar^2 k/m + V_0)^2}\,,\\
\sigma(E) &= \frac{2\hbar^2 k V_0/m}{(\hbar^2 k/m + V_0)^2}\,,
\end{aligned}
\tag{1}
$$

where k is the wave vector and m the effective mass. It is readily seen that as V_0 increases from zero, $\sigma(E)$ rises to a maximum of 0.5 falling off to zero thereafter, whereas $R(E)$ increases monotonically to one. This clearly shows the dual role of the imaginary potential as an absorber and as a reflector. At this point it is apt to note a physical realization of such an absorptive potential. It simply amounts to opening n additional branches (outgoing channels) through wich the probability current leaks out to infinity. Indeed, one can readily verify from the Griffith[8] boundary condition at the branch point for the n identical channels that

$$
R(E) = (\frac{n}{n+2})^2 \qquad T(E) = (\frac{2}{n+2})^2 \qquad \sigma(E) = \frac{4n}{(n+2)^2}\,. \tag{2}
$$

Here n effectively measures the strength of absorption. Again as $n \rightarrow \infty$, the absorption $\sigma(E)$ rises from 0 to a maximum of 0.5 at $n = 2$ and then falls off to 0.

We now show that the main features of this elementary example carry over to the more interesting case of the double-barrier heterostructure as far as the dual role of the imaginary potential is concerned. Indeed, consider a symmetrical structure of two equal barriers of height $0.4eV$ and width $50\mathring{A}$ and a well $50\mathring{A}$ wide with a constant imaginary potential $V(x) = -iV_i$. We show in Fig. 1 the variation of the reflection, transmission and the absorption coefficients as function of the strength V_i at the resonance energy. We can see from Fig. 1 that the absorption is non-monotonic as function of the imaginary potential and shows a maximum value of 0.5, this corresponds to $\Gamma^i \approx \Gamma^e$. Here Γ^e and Γ^i stand for the elastic resonance width and the inelastic width, respectively. The full width Γ is the sum $\Gamma = \Gamma^e + \Gamma^i$ and for the parameters above[9] $\Gamma^i = 1.82\, V_i$.

Consider now for comparison a non-resonant situation. That of an extreme "double-barrier" with zero height, i.e., just a strip of imaginary potential of width $50\AA$, for the same incident energy as for the resonant case above. For this case Fig. 2 shows the same general features. However the value of V_i needed to reach maximum absorption is much larger than that for the resonant double-barrier Fig. 1. This has a simple physical interpretation. For the non-resonant case there are two competing effects, the rise of absorption due to increase of V_i and the rise of reflection due to mismatch caused by this same increase. For small values of V_i the first effect dominates leading to increasing absorption with V_i, while for large V_i reflection dominates leading to decreasing absorption. Hence the maximum in absorption.

For the resonance case there is an additional crucial effect associated with the dwell time of the electron in the resonant state, which depends sensitively on V_i (while in the non-resonant case the traversal time is not expected to be a sensitive function of V_i). The dwell time of the electron is the time during which V_i acts absorptively. As V_i increases from zero but keeping $\Gamma^i (\propto V_i)$ still small compared to Γ^e, the dwell time is determined by Γ^e and remains nearly constant. Thus absorption increases essentially linearly with V_i. As Γ^i becomes comparable with Γ^e the dwell time itself begins to diminish and with further increase of V_i this effect will take over halting the increase of the absorption σ. For even larger values of V_i reflection becomes the dominant effect and absorption decreases eventually to zero.

In this work we have tried to bring out the dual role of an imaginary potential –absorptive and reflective– in the context of tunneling. Our main result is that absorption is not a monotonically increasing function of the absorptive potential strength because of the concomitant reflection caused by the mismatch. The competition between these two effects leads to a maximum in absorption as function of V_i in general. The most efficient resonant absorber corresponds to a very weak absorptive potential acting over long times as insured by a very sharp resonance. Simple timescale consideration leads to

$$\sigma = \frac{\Gamma^i}{\Gamma^e + \Gamma^i} \rightarrow \frac{1}{2}$$

as $\Gamma^i \rightarrow \Gamma^e$.

Finally, we would like to remark a general aspect of this problem. As mentioned before, these electronic features have obvious photonic counterparts. Indeed, many of the results are a rediscovery of facts well known in optics. There is, however, a fundamental difference in the case of light because of its bosonic nature. Thus a coherent radiation from a laser is an eigenstate of the annihilation operator and therefore the removal of a photon by an absorptive potential (complex refractive index) leaves it in that coherent sate. For an electron –a fermion– in contrast, a realistic inelastic scattering will always cause decoherence. This decoherence effect is missing from the phenomenological treatments using imaginary potentials.

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References

1. B. Ricco and M. Ya. Azbel' Phys. Rev. **B 29**, 1970 (1984). For a review, see F. Capasso and R. Datta, Phys. Today **43**, No. 2, 74 (1990).

2. A. D. Stone and P. A. Lee, Phys. Rev. Lett. **54**, 1196 (1985).

3. T. Weil and B. Vinter, Appl. Phys. Lett. **50**, 1281 (1987).

4. M. Jonson and A. Grincwajg, Appl. Phys. Lett. **51**, 1729 (1987).

5. M. Büttiker, IBM J. Res Dev. **32** , 63 (1988).

6. S. C. Kan and A. Yariv, J. Appl. Phys. **67**, 1957 (1990).

7. A. Sa'ar, S. C. Kan, and A. Yariv, J. Appl. Phys. **67**, 3892 (1990).

8. S. Griffith, Trans. Faraday Soc **49**, 345, 650 (1953).

9. G. García-Calderón and A. Rubio, unpublished.

Figure captions

Fig. 1. The absorption $\sigma(E_r)$, reflection $R(E_r)$ and transmission $T(E_r)$ coefficients at resonance energy E_r vs the strength V_i of a constant imaginary potential localized in the well for a double barrier structure with barrier heigths of $0.4eV$ and barriers and well widths of $50\mathring{A}$.

Fig. 2. The absorption $\sigma(E_r)$, reflection $R(E_r)$ and transmission $T(E_r)$ coefficients vs the strength V_i of a constant imaginary potential strip $50\mathring{A}$ wide. The energy is the resonance energy E_r of the structure in Fig. 1 .

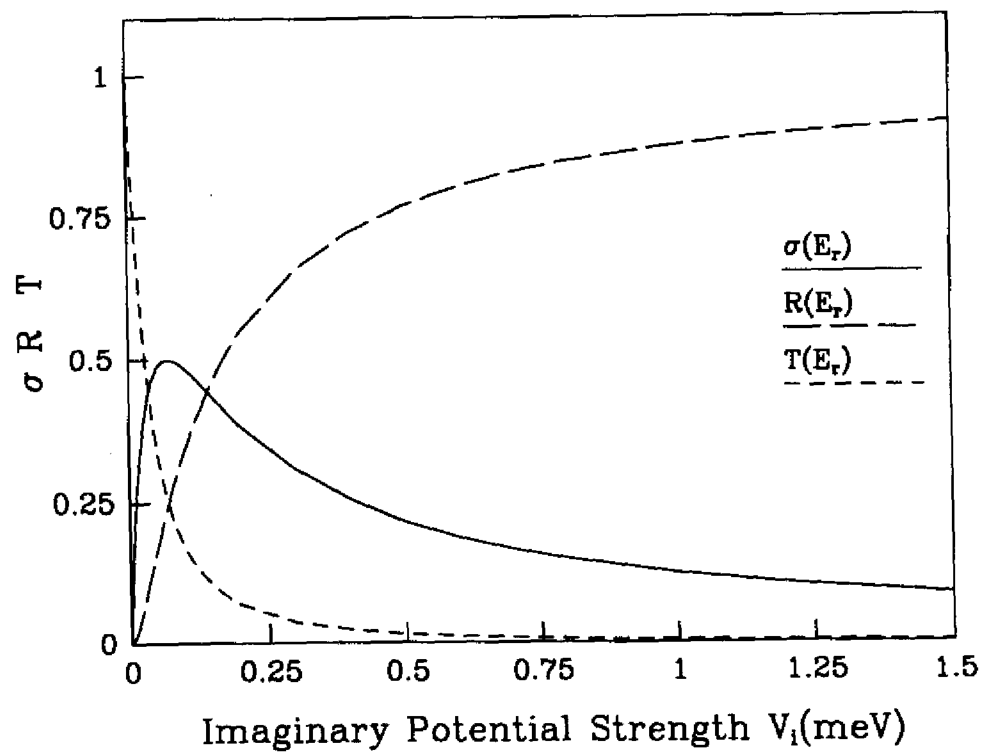
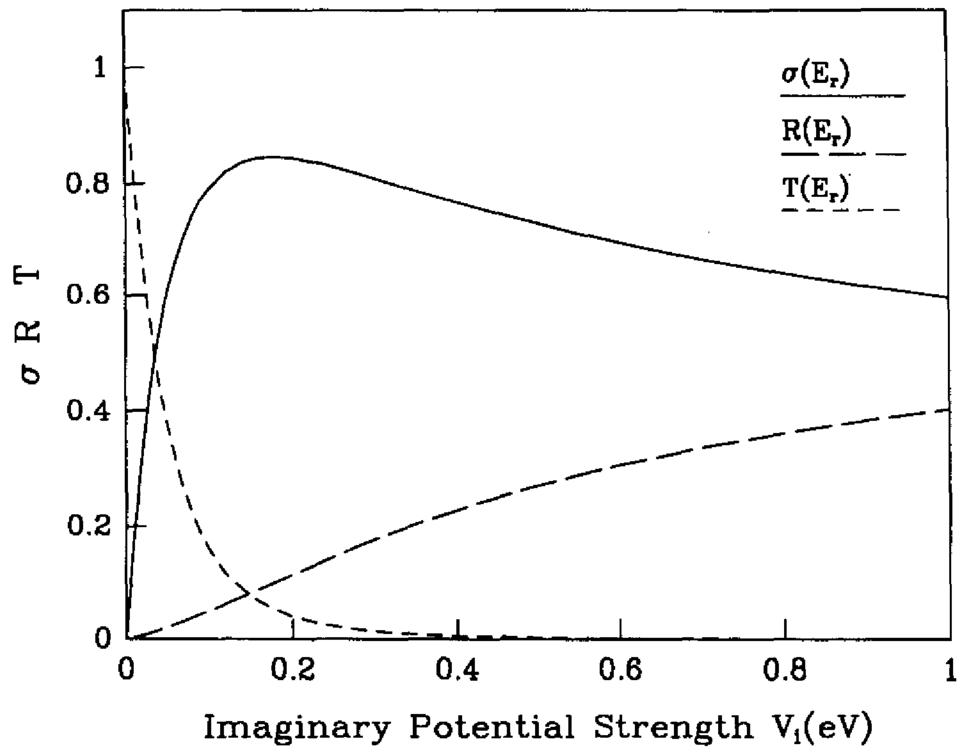


Fig.1



σ(E_r)
R(E_r)
T(E_r)
σ R T
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Imaginary Potential Strength V_i(eV)

Fig.2