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LETTER TO THE EDITOR

Compensation effect of one-dimensional disordered potential wells and barriers in the presence of an electric field

N Zekri†§, M Schreiber† and R Ouasti‡

† Institut für Physik, Technische Universität Chemnitz-Zwickau, D-09107 Chemnitz, Germany
‡ Laboratoire de Physique Electronique du Solide USTO, Département de Physique, BP 1505, Oran El M'naouer, Algeria

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Abstract. We study the origin of the compensation in disordered mixed systems of the Wannier–Stark ladder effects observed previously as strong jumps of the transmission coefficient in ordered and disordered systems with potential wells and barriers subjected to a bias voltage. The one-dimensional Kronig–Penney model is used to investigate this problem by means of the transmission coefficient. We found that the band spectrum of the systems with barriers is shifted in comparison with the corresponding spectra of those with wells. Therefore the delocalization of each system in an electric field corresponds to the localization of the other. We found also that the disorder conserves the bandwidth of the ordered system if the average potential strength corresponds to the potential strength of this system.

The electronic properties of one-dimensional (1D) systems have been the subject of a continuous interest in solid state physics [1–9]. Among the new technological advances, in particular the ability to fabricate man-made thin wires and 1D heterostructures led to very interesting electronic features [10, 11].

The disorder has been shown for a long time to localize the electronic states [1, 2] and one- and two-dimensional disordered systems were expected to become insulators [3]. However, recently, some models of disorder introducing correlations [7, 9] and non-linearity [8] yielded extended states for particular energies, meaning that the disorder can also provide constructive quantum interferences.

The electric field has been found to delocalize the electronic states of disordered 1D systems [4–6] while in ordered systems a Wannier–Stark ladder effect [12] breaks the quasi-continuum levels leading to their localization and to the formation of singular resonances observed in the transmission coefficient by jumps. In such cases the differential resistance of the system becomes negative.

However, in disordered systems mixing uniformly both potential barriers and wells, the latter effect in an electric field has not been clearly seen in the transmission coefficient (T) [4–6]. Recently [13], we found strong jumps of T in disordered systems with either wells or barriers corresponding to this effect and occurring regularly at the Brillouin zone edges

$$E + eFL = n^2(\pi/a)^2 \tag{1}$$

§ Permanent address: Laboratoire de Physique Electronique du Solide USTO, Département de Physique, BP 1505, Oran El M'naouer, Algeria.

where E is the electron energy, e the electron charge, F the electric field and L the chain length with a lattice parameter a. Furthermore, we found that for lengths before the first jump of T, the field increases the localization for the systems with potential wells instead of delocalizing them. The transmission coefficient in these cases fits the following form well:

$$T \propto \exp\left(-L^{\beta(F)}\right) \qquad \beta(F) > 1 \text{ with } \beta(0) = 1 \tag{2}$$

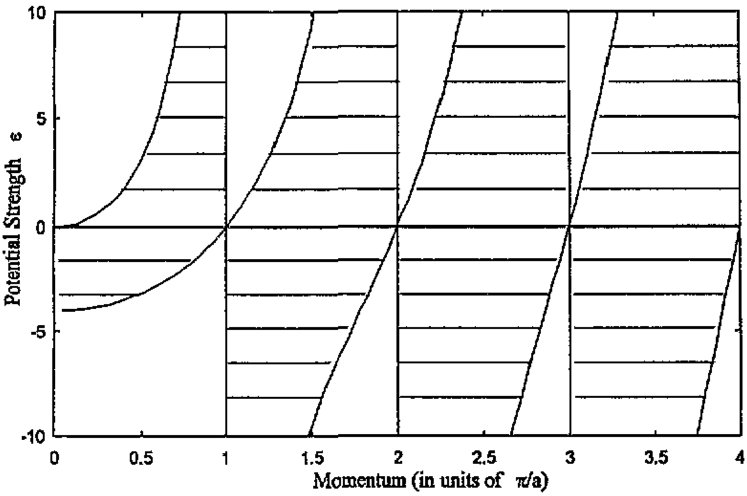

Figure 1. Energy spectrum of the ordered systems with wells or barriers for different potential strengths as a function of the momentum in units of π/a. Hatched regions correspond to the allowed bands.

More recently [14], we showed that this effect does not occur for all systems with wells and depends on the electron energy and the disorder (or the potential strength in ordered systems). Furthermore, in examining the effect of the electric field on ordered systems with potential wells, we found that the jumps of T and the 'superlocalization' (given by (2)) yield at opposite sides of the allowed bands. The former effect occurs in the allowed bands near the Brillouin zone edges (where resonant tunnelling yields a transmission coefficient identical to unity). In this case the energy levels are shifted by the field and discrete resonant states appear. Furthermore, the transmission coefficient oscillates with a decreasing period with increasing chain length. The superlocalization effect occurs in the gaps near the other edge of the allowed bands.

In this letter, we examine such effects in the systems with barriers where the bands are seen to be shifted in comparison with those in the systems with wells. The effect of the disorder on the band structure of these systems is also shown by means of the transmission coefficient. This leads us to study why the jumps in the transmission coefficient that were observed in the systems with wells and barriers separately are compensated in the disordered mixed systems.

The model has been described in detail previously [13, 14]. We consider a linear finite chain of N atoms equally spaced with δ-peak potentials of random strengths ε_n uniformly

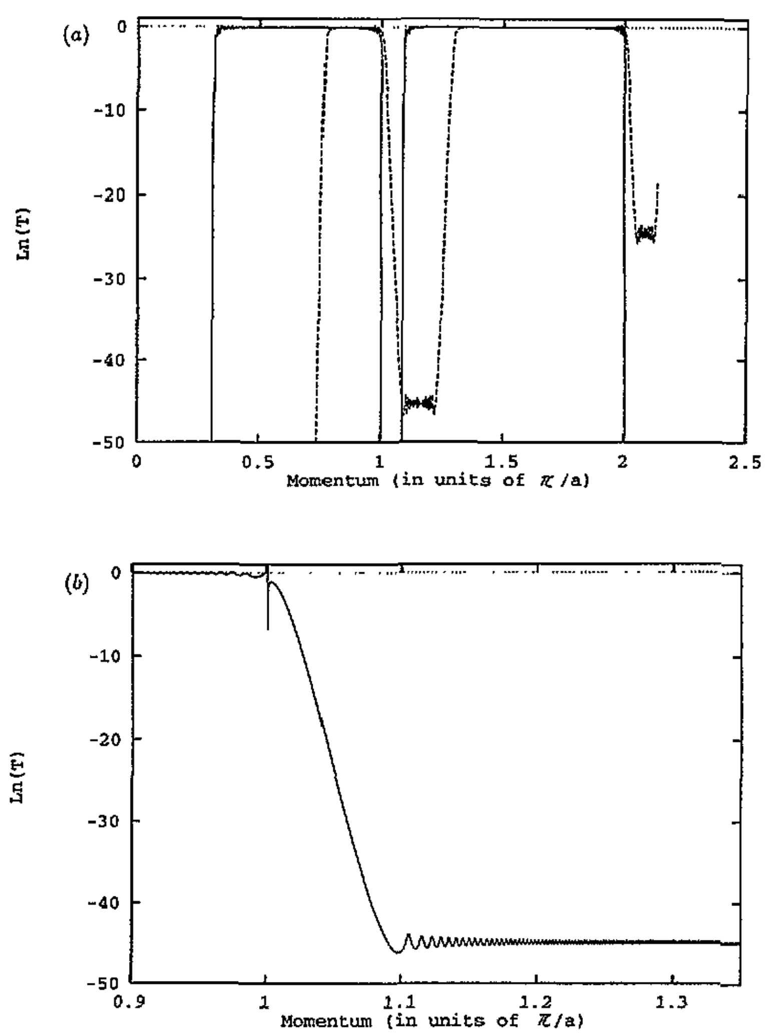

Figure 2. Effect of the electric field on the ordered systems with barriers ($\varepsilon = 1$). Transmission coefficient versus the momentum in units of π/a. The momentum $k_n = \sqrt{E + FL}$ varies by fixing the field and varying: (a) the energy for $L = 500$, $F = 0$ (solid curve) and $F = 0.01$ (dashed curve); (b) the chain length for $E = 8$ and $F = 0.01$.

distributed in the three following cases:

$$\begin{aligned} \varepsilon_n &\in [-W,\ 0] && \text{(random wells)} \\ \varepsilon_n &\in [0,\ W] && \text{(random barriers)} \\ \varepsilon_n &\in [-W/2,\ W/2] && \text{(mixed systems)} \end{aligned} \tag{3}$$

where W is the disorder. A bias voltage $V = FL$ is applied to the chain with a length $L = N$ (the electron charge e and the lattice parameter a are assumed here to be unity and the energy is measured in units of $\hbar^2/2m$). The two ends of such a chain are assumed to be connected to ideal conductors in which the states are plane waves. The Schrödinger equation in the Kronig–Penney model is discretized into a finite difference equation by means of the Poincaré map representation in the ladder approximation:

$$\Psi_{n+1} = \left[\cos(k_{n+1}) + \frac{k_n \sin(k_{n+1})}{k_{n+1}\sin(k_n)}\cos(k_n) + \varepsilon_n \frac{\sin(k_{n+1})}{k_{n+1}}\right]\Psi_n - \frac{k_n \sin(k_{n+1})}{k_{n+1}\sin(k_n)}\Psi_{n-1}. \tag{4}$$

The ladder approximation is valid only for small fields $Fa \ll E$. For strong fields we can use the well known multi-step-function approximation [15] which is very accurate and consumes less computer time than the exact solutions of the Schrödinger equation (which are like Airy functions).

The transmission coefficient is the quantity of interest here and can be obtained from the numerically computed wavefunctions in a straightforward manner [13].

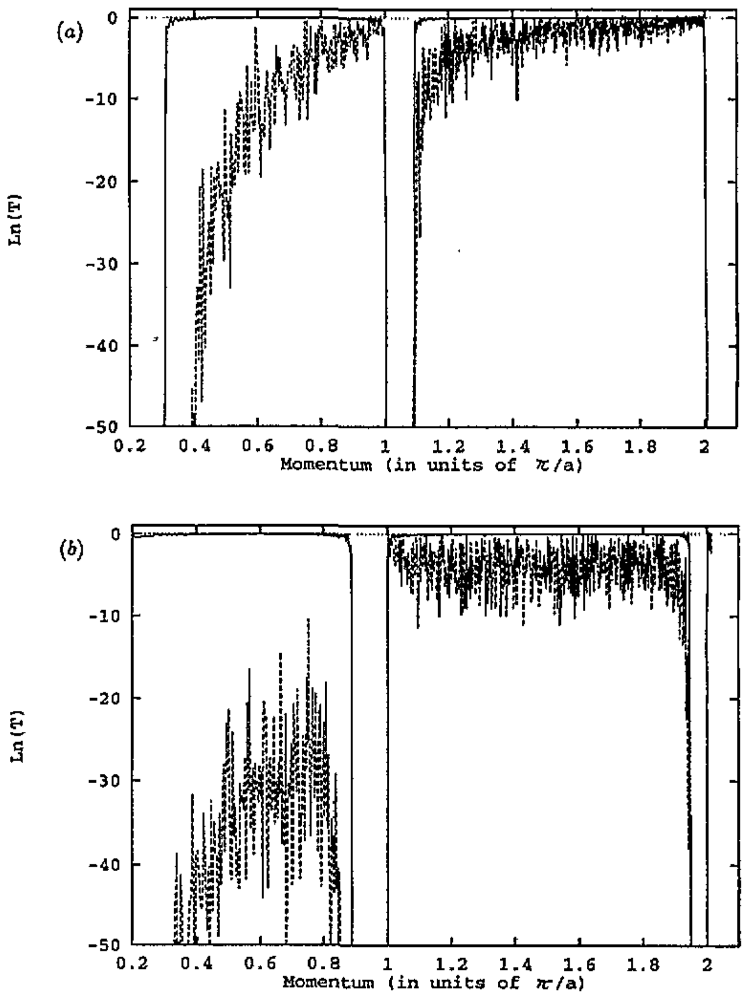

Figure 3. Effect of the disorder on the transmission coefficient for $E = 8$, comparing ordered systems, $|\Sigma| = 1$ (solid curve), and disordered systems, $|\langle\Sigma\rangle| = 1$ (dashed curve). (*a*) Systems with barriers; (*b*) systems with wells.

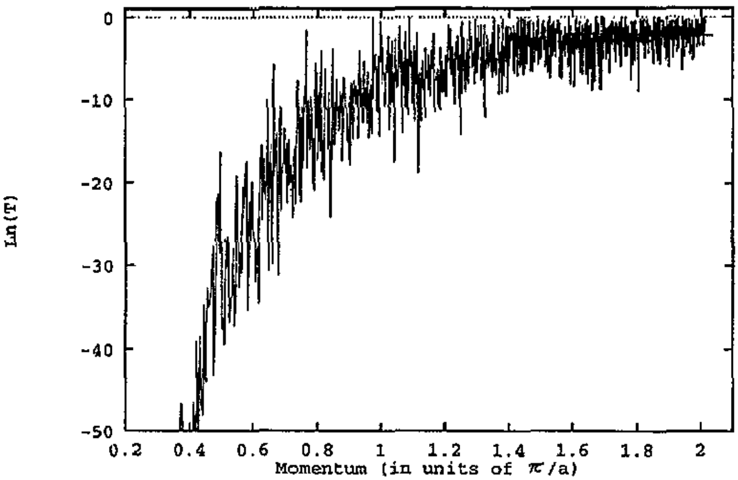

Figure 4. Transmission coefficient as a function of the momentum in units of π/a for disordered mixed systems with $W = 2$.

In the absence of an electric field, the band width of ordered systems is shown in figure 1 as a function of the potential strength W (i.e., $\varepsilon_n \equiv W$). We can see from this figure that the edges of the Brillouin zone (vertical solid lines) correspond to the beginnings of the allowed bands in the systems with wells while they correspond to the ends of the allowed bands in systems with barriers. This is also clearly shown for the transmission coefficient in figures 2(a) and (b) (solid curves) where the gaps correspond to an abrupt drop.

In applying an electric field to the systems with barriers, we see the two effects (the jumps of T and the superlocalization) both above the Brillouin zone edges (figure 2(a)). The transmission coefficient first decreases in the gap, and in the allowed bands it oscillates and a Wannier–Stark ladder effect results (figures 2(a) and (b). In the systems with wells, these effects have been found on both sides of the Brillouin zone edges. Therefore such effects are shifted in the systems with barriers in comparison with those with wells.

On the other hand, in figure 3 the disorder decreases the transmission coefficient inside the allowed bands and then discrete resonances appear due to the localization effect. This effect occurs both for the systems with barriers (figure 3(a)) or wells (figure 3(b)). We can see also from figure 3 that the gap is not affected by the disorder if the potential strength of the ordered system is equal to the average potential strength of the disordered one. Furthermore, these figures confirm that in the allowed bands the transmission coefficient approaches unity at the Brillouin zone edges independently of the disorder [14].

Therefore, in combining the effects of the disorder and the electric field in the systems with barriers and wells, we obtain a compensation of the jumps of T in the disordered mixed systems because the region of the delocalization of each pure system corresponds to the region of localization of the other one. Indeed this is clearly observed in figure 4 where the gaps have disappeared. Although it seems to remain in these systems a small decrease of the transmission coefficient corresponding to the first jump is expected when applying an electric field. Obviously, this decrease disappears for higher energies. This is the reason why Cota *et al* [6] have observed only one jump.

In conclusion, by examining separately systems with wells or barriers we have observed that the band spectrum of each system is shifted in comparison with the other one. Therefore in an electric field the localization effect in each system is compensated by the delocalization of the other one when they are mixed. Furthermore, the jumps of T have been shown to decrease when the electron energy increases [13]. This is the reason why only one jump has been observed previously in the mixed systems [6].

However this effect may be controlled by varying the concentration of one type of potential (barriers or wells). It is also interesting to study this effect for potentials with a finite width. This shall be the subject of forthcoming work.

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