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2003 J. Phys.: Condens. Matter 15 L649

(http://iopscience.iop.org/0953-8984/15/43/L02)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **15** (2003) L649–L653 PII: S0953-8984(03)68661-3

LETTER TO THE EDITOR

A simple electron multiplexer

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Received 9 September 2003
Published 17 October 2003
Online at stacks.iop.org/JPhysCM/15/L649

Abstract

We present a simple multiplexing device made of two atomic chains coupled by two other transition metal atoms. We show that this simple atomic device can transfer electrons at a given energy from one wire to the other, leaving all other electron states unaffected. Closed-form relations between the transmission coefficients and the inter-atomic distances are given to optimize the desired directional electron ejection. Such devices can be adsorbed on insulating substrates and characterized by current surface technologies.

The directional ejection of electrons [1–3] from one electronic guide to another is now intensively investigated, as such transfer processes are particularly important in wavelength multiplexing and in telecommunication routing devices.

A device enabling a directional ejection of quasi-particles should let the quasi-particles of all but one wavelength travel without perturbation in the input waveguide or wire. At the same time the quasi-particle of one selected and well-defined wavelength is expected to be transferred to the other wire with a phase shift as the only admitted distortion. To meet the above requirements as closely as possible an appropriate coupling device should be designed.

In this letter we describe a simple device which, under certain conditions, realizes the directional transfer of one electron with a good selectivity. The device is depicted in figure 1. It consists of two atomic chains made out of a periodic sequence of equidistant transition metal atoms. The distance between the neighbouring atoms within each chain is a. These input and output wires go respectively through atoms $(1, 2)$ and $(3, 4)$. The distance between atoms $(1, 2)$ and $(3, 4)$ is La, where the integer L is greater than 1, as there can be $(L - 1)$ atoms between atoms 1 and 2 and between atoms 3 and 4. Two additional atoms 5 and 6

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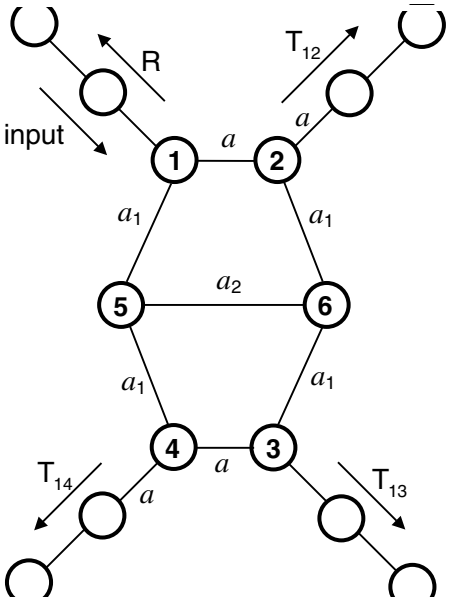

Figure 1. One possible multiplexer geometry made out of identical transition metal atoms. The nearest neighbour distance within the atomic chains is a. The two clusters 5 and 6 are a_2 apart and they lie at a distance a_1 from the clusters $(1, 4)$ and $(2, 3)$ respectively. In this illustrative figure $L = 1$, $a_1/a = 1.5$ and $a_2/a = 2$.

of a different transition metal from those of the atomic chains are deposited between the two chains. The atom 5 lies at an equal distance a_1 from the atoms 1 and 4. The same distance and overlap integrals are supposed to exist between the atoms 6 and respectively atoms 2 and 3. The distance between atoms 5 and 6 is called a_2. Being so defined the device shows two perpendicular mirror symmetry planes. We suppose this atomic device is adsorbed on an insulating substrate.

Each atom is characterized by its electron level atomic energy: E_0 within the chains and E_0' for atoms 5 and 6. We only retain here the nearest neighbour overlap integrals and neglect damping effects. A thorough discussion of the validity of these assumptions can be found in [4]. The electron dispersion relation in such an infinite atomic chain is [4]

$$E(k) = E_0 - 2\beta\cos(ka), \tag{1}$$

where k is the Bloch wavevector of the chain and β the first nearest neighbour overlap integral.

The interactions β_i involving atoms 5 and 6 can be related to the intra-chain interaction β and distance a by the empirical relation [5]

$$\beta_i = \beta\exp\left[\gamma\left(1 - \frac{a_i}{a}\right)\right], \qquad i = 1 \text{ and } 2. \tag{2}$$

Generally, as a result of scattering processes, a reflected electronic wave will appear at node 1 along with three transmitted waves at nodes 2, 3 and 4 respectively.

The corresponding reflection and transmission coefficients are functions of the energy E or equivalently the propagation vector k defined in equation (1). They are conveniently expressed by the following formulae (see [3] for similar considerations):

$$R = T_{11} = |z_1 + z_2 + z_3 + z_4 - 1|^2, \tag{3}$$

$$T_{12} = |z_1 + z_2 - z_3 - z_4|^2, \tag{4}$$

$$T_{13} = |z_1 - z_2 + z_3 - z_4|^2, \tag{5}$$

$$T_{14} = |z_1 - z_2 - z_3 + z_4|^2, \tag{6}$$

where

$$z_n = \frac{2\mathrm{i}}{4(\mathrm{i} + y_n)}, \qquad n = 1, 2, 3, 4, \tag{7}$$

and

$$y_1 = y_2 - \frac{2\beta_1^2}{F(E_0 - E_0' - 2\beta\cos(ka) + \beta_2)}, \tag{8}$$

$$y_2 = \tan\left(\frac{kLa}{2}\right), \tag{9}$$

$$y_3 = -\left[\tan\left(\frac{kLa}{2}\right)\right]^{-1}, \tag{10}$$

$$y_4 = y_3 - \frac{2\beta_1^2}{F(E_0 - E_0' - 2\beta\cos(ka) - \beta_2)}. \tag{11}$$

The quantity F is given by the following expression:

$$F = \beta\sin(ka). \tag{12}$$

One notes that the reflection into the atomic chain 1 and the transmission into chain 4 are always equal for every wavelength in this kind of electron device, independently of all the parameters,

$$R = T_{14}. \tag{13}$$

The total electron transfer from the input 1 to the output 3, i.e. $R = 0$, $T_{12} = 0$, $T_{13} = 1$ and $T_{14} = 0$, can be realized exactly at the electron level energy of the isolated atom, which leads to the following condition:

$$2\beta\cos(k_0a) = E_0 - E_0' \tag{14}$$

provided that

$$\beta_2 = \frac{\beta_1^2}{\beta}\frac{\sin(k_0La)}{\sin(k_0a)}. \tag{15}$$

The transferred electron has some width in energy around E_0' or in k around k_0. If one wishes the corresponding peak in T_{13} to be symmetric, then one has to fulfill another condition, namely

$$Lk_0a = (1 + 4n_0)\frac{\pi}{2}, \qquad n_0 = 0, 1, 2, \ldots. \tag{16}$$

The phase factor between the electronic wave directionally transferred to atom 3 with respect to the incident wave at atom 1 is

$$\mathrm{e}^{\mathrm{i}\varphi} = -\mathrm{e}^{\mathrm{i}k_0La}. \tag{17}$$

Let us also define the quality factor associated with the linewidth of the transferred signal by

$$Q(k_0a) = \frac{k_0a}{\Delta(k_0a)}, \tag{18}$$

where $\Delta(k_0a)$ is the width of this signal for $T_{13}(ka) = 0.5$.

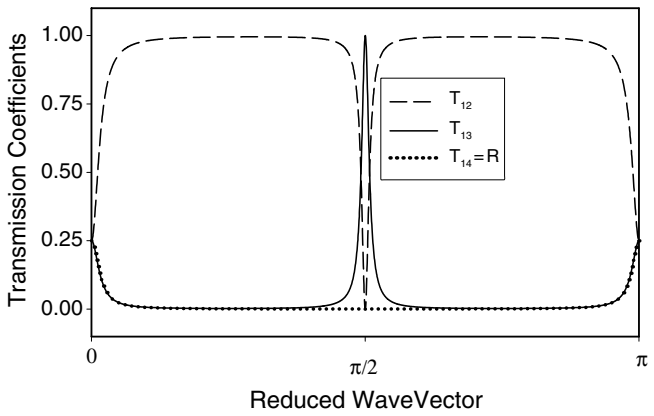

Figure 2. Transmission coefficients T_{13}, T_{12} and T_{14} $(=R)$ as a function of the reduced wavevector ka for the system of figure 1 with parameters $a_1/a = 1.5$, $a_2/a = 2$ and $\gamma = 3$.

An approximated value of this quality factor is

$$Q(k_0 a) = (1 + 4n_0)\frac{\pi}{L}\frac{\beta}{\beta_2}\sin\left[(1 + 4n_0)\frac{\pi}{2L}\right]. \tag{19}$$

With the above assumptions, the electronic currents I_j for coherent electron transport from atom 1 to atom $j = (2, 3, 4)$ are given by the Landauer–Büttiker formula [6]:

$$I_j = \frac{2e}{h}\int_0^\infty T_{1j}(E)[f_j(E) - f_1(E)]\,\mathrm{d}E, \tag{20}$$

where

$$f_j(E) = \left[1 + \exp\left(\frac{E - \mu_j}{k_\mathrm{B}T}\right)\right]^{-1} \tag{21}$$

is the Fermi function for atom j and the potentials μ_j are chosen such that $\mu_2 = \mu_3 = \mu_4 < \mu_1$. For temperature T such that $k_\mathrm{B}T \ll (\mu_1 - \mu_2)$, $(\mu_1 - \mu_2)$ being the bias potential applied between the two external electrodes, equation (20) reduces to

$$I_j = \frac{2e}{h}T_{1j}(E_\mathrm{F})(\mu_1 - \mu_2), \tag{22}$$

where E_F is the Fermi energy. In these conditions, the electron current will flow from atom 1 to atom 2 in all situations of weak coupling between the two chains ($\beta_1 \ll \beta$), with one exception. When the coupling device is tuned so that the conditions given by equations (14) and (15) are fulfilled and $E_0' = E_\mathrm{F} = (\mu_1 + \mu_2)/2$, the electron current will flow from terminal 1 to terminal 3. This system therefore acts as an electron directional coupler.

To give an illustrative and at the same time realistic example complying with the above assumptions, we consider tungsten (W) atoms for all the device atoms and $L = 1$. W chains have a half-filled d band; self-consistency problems can therefore be neglected with a good precision [4]. The other distances involved for $L = 1$ are such that (equations (2) and (15))

$$\frac{a_2}{a} = \frac{2a_1}{a} - 1. \tag{23}$$

Figure 2 presents the transmission coefficients T_{13}, T_{12} and T_{14} $(=R)$ as a function of the reduced wavevector ka in the whole range of the transmission band of the wires, for $a_1/a = 1.5$, $a_2/a = 2$ and $\gamma = 3$. One notices the reflection symmetry with respect to $ka = \pi/2$ as well as

the common value 1/4 of all the transmission coefficients at the band borders. The selectivity increases with γ and with a_1 (see equations (19), (2) and (23)).

The symmetry of the device and the fact that all the atoms involved in the example studied here are identical underlies the symmetry of the curves in figure 2. A shift of the directional ejection peak would occur if the atoms 5 and 6 were different from those in the chains since, as a rule, the directional ejection takes place at the electron level atomic energy E_0' of the coupling atoms. This indicates how the directional ejection electron wavelength may be controlled by selecting the appropriate parameters of the device. Further modifications will be brought about in forthcoming investigations by taking into account further nearest neighbour interactions and damping. Simulations are in progress to reveal other features of the device.

Two of us (HA and PZ) gratefully acknowledge the hospitality of the UFR de Physique, Université de Lille I. The authors acknowledge 'Le Fond Européen de Développement Régional' (FEDER) and 'Le Conseil Régional Nord-Pas de Calais' for their support.

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