第27卷 第4期
2006年4月

半 导 体 学 报
CHINESE JOURNAL OF SEMICONDUCTORS

Vol.27 No.4
Apr.,2006

Transport Properties of Two Coupled Quantum Dots Under Optical Pumping*

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Abstract: Using the Keldysh-Green function, we present a theoretical study on the electron transport properties of two coupled quantum dots under optical pumping. Plateaus in the I-V curve and resonant peaks in the transmission coefficient occur and can be explained by the local electron density of states in the quantum dots. The effects of the optical pumping frequency and intensity on the transport properties of the system are also discussed. The electron dynamical localization phenomenon occurs when the optical pumping frequency is equal to the discrete hole energy level. This result can be used to realize optical control switches.

Key words: Keldysh-Green function; optical pumping; quantum dot; electron transport; dynamical localization
PACC: 7200; 7320D
CLC number: O472^{+}.4 **Document code:** A **Article ID:** 0253-4177(2006)04-0598-06

1 Introduction

Due to recent developments in microfabrication technology, such as electron beam lithography and molecular beam epitaxy, low-dimension artificial semiconductor structures (including quantum dots, quantum wells, and quantum wires) as small as a few hundred angstroms can be successfully fabricated. Mesoscopic electronic transport basically deals with electron transport across such small systems, typically with dimensions comparable to phase-randomizing or the inelastic coherence length L_Φ, which can be as large as 1～3μm for a 2D layer transport channel of a MOSFET at $T = 4.2$K. When the transport dimension reaches such a characteristic size, namely, the charge-carrier inelastic coherent length L_Φ, and the charge-carrier confinement dimension approaches the Fermi wavelength, the macroscopic Ohm's law may not hold. The main reasons are as follows. First, the length of the mesoscopic system is smaller than that of electronic phase breaking, so that electrons can keep their phase memory and electron wave coherence can play an important role. Second, electrons are confined in certain dimensions, giving rise to quantized electronic energy levels. In fact, mesoscopic physics has been widely researched[1] for the last two decades. A wealth of interesting phenomena have already been revealed. Typical examples observed in metallic wires are conductance quantization[2,3] across a quantum point contact, universal conductance fluctuation[4], the Aharonov-Bohm[5,6] oscillation of conductance through a ring with a magnetic flux, and the coulomb-blockade[7,8] effect in microtunnel junctions.

Very recently, there has been a growing interest[9～24] in understanding how external time-dependent perturbations affect the phase coherence of low-dimensional semiconductor systems. This interest stems from recent progress in several experimental techniques[25,26]. External time-dependent perturbations affect the phase factor of the wave function in different regions of the system, leading to the well-known photon-assisted tunneling process, in which an electron can go through the system by emitting or absorbing multiple photons. This process is responsible for side-band peaks in the curve of conductance versus the gate voltage and for a plateau structure in the current-voltage (I-V) curves. In these low-dimensional structures, the phase-destroying scattering process is considerably reduced, and interaction with external time-dependent fields in low-dimensional systems leads in many cases to completely new forms of electronic transport, in which the time domain coherence also

* Project supported by the National Natural Science Foundation of China (Nos. 90303011, 10474034, 60390070)

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Received 14 December 2005, revised manuscript received 25 January 2006

gives rise to many novel phenomena. Among these are the dynamical localization observed in superlattices, ac-induced absolute negative conductance, electron pumps realized in different nanostructures, and the very recent microwave studies demonstrating quantum coherence in double quantum dots.

In this paper, we study the electron transport properties of two coupled semiconductor quantum dots under optical pumping. Using the Keldysh-Green function, we can solve the time-dependent quantum transport problem analytically. Plateau structures in the *I-V* curve occur and can be explained by the local electron density of states in quantum dots. The effects of the optical pumping frequency and intensity on the transport properties of the system are also discussed. When the frequency of the optical pumping (relative to the Fermi level of the leads) is equal to the discrete hole energy level, the electron dynamical localization phenomenon occurs. This result can be used to design optical control switches.

2 Model and calculations

Consider a system that consists of two coupled semiconductor quantum dots, with left and right leads. There is an interband transition in each dot under optical pumping at frequency ω. Since the holes are much heavier than the electrons in the quantum dots, we need only to consider electron transport in this problem. In other words, the holes are only spectators and do not participate as charge carriers, just as in Ferreira's experiment[27]. Electrons are allowed to tunnel from the left lead to the right lead via the two coupled quantum dots. The Hamiltonian of this system is then

$$H = H_L + H_R + H_{dots} + H_T \tag{1}$$

where

$$H_L = \sum_k \varepsilon_{kL} a_{kL}^\dagger a_{kL} \tag{2}$$

$$H_R = \sum_k \varepsilon_{kR} a_{kR}^\dagger a_{kR} \tag{3}$$

$$H_{dots} = \sum_{i=1,2} [\varepsilon_{ei} c_i^\dagger c_i + \varepsilon_{hi} d_i^\dagger d_i] + t c_1^\dagger c_2 + t c_2^\dagger c_1 + \sum_{i=1,2} [\lambda \exp(i\omega t) c_i d_i + \lambda \exp(-i\omega t) d_i^\dagger c_i^\dagger] \tag{4}$$

$$H_T = \sum_k [T_{kL} a_{kL}^\dagger c_1 + T_{kR} a_{kR}^\dagger c_2 + c.c] \tag{5}$$

where H_L and H_R are the Hamiltonians of the left and right leads, which can be described by the free electron model. The corresponding annihilation operators are a_{kL} and a_{kR}, respectively. H_{dots} is the Hamiltonian of the two coupled semiconductor quantum dots under the interband optical pumping[28]. c_i and d_i are the electron and hole annihilation operators for the ith quantum dot. Note that we only consider interband transitions with dipole moment d in the rotating-wave approximation. The parameters λ, d, and the electric-field strength E should satisfy the relation $\lambda = Ed$. Additionally, since the sizes of the quantum dots are very small and the frequency of the electromagnetic field ω is not very high, the inequality[29] $E \gg \omega^2 \hbar c / c^2$ is easily satisfied. It is reasonable to treat the optical pumping field as a semi-classical field. The last Hamiltonian describes the hopping term between the leads and the quantum dots with hopping matrix elements T_{kL} and T_{kR}.

We now calculate the electronic current through the left lead, which is defined as (we use $\hbar = 1$ in the whole paper)

$$I_L(t) = -q \int dt_1 [G_{11}^r(t,t_1)\Sigma_L^<(t_1,t) + G_{11}^<(t,t_1)\Sigma_L^a(t_1,t) - \Sigma_L^<(t,t_1)G_{11}^a(t_1,t) - \Sigma_L^r(t,t_1)G_{11}^<(t_1,t)] \tag{6}$$

where the related Green's functions in the Keldysh formulation can be defined as

$$G_{11}^{r,a}(t_1,t_2) = \mp i\theta(\pm t_1 \mp t_2)\langle\{c_1(t_1), c_1^\dagger(t_2)\}\rangle \tag{7}$$

$$G_{11}^<(t_1,t_2) = i\langle c_1^\dagger(t_2) c_1(t_1)\rangle \tag{8}$$

and the corresponding self-energies due to the leads are of the form

$$\Sigma_L^{r,a,<}(t_1,t_2) = \sum_k T_{kL}^* T_{kL} g_{kL}^{r,a,<}(t_1,t_2) \tag{9}$$

in which $g_{kL}^{r,a,<}$ are the retarded, advanced and lesser Green's functions for the noninteracting left lead, respectively.

By introducing the double-time Fourier transformation

$$F(E_1,E_2) = \iint dt_1 dt_2 F(t_1,t_2)\exp[i(E_1 t_1 - E_2 t_2)] \tag{10}$$

the charge current is expressed as

$$I_L(t) = -q \iint \frac{dE_1}{2\pi} \times \frac{dE_2}{2\pi} \exp[-i(E_1 - E_2)t] \times [G_{11}^r(E_1,E_2)\Sigma_L^<(E_2) + G_{11}^<(E_1,E_2)\Sigma_L^a(E_2) - \Sigma_L^<(E_1)G_{11}^a(E_1,E_2) - \Sigma_L^r(E_1)G_{11}^<(E_1,E_2)] \tag{11}$$

In order to calculate the charge currents, one has to know the expressions of both the retarded Green's function and lesser Green's function for the quantum dots. Since the lesser Green's function and retarded Green's function are related by the Keldysh equation $G^{<} = G^{r}\Sigma^{<}G^{a}$, the core problem is reduced to calculating the retarded Green's function. In general, a perturbation approach is needed to solve a time-dependent problem. Fortunately, for the Hamiltonian we consider here, the retarded Green's functions for the quantum dots can be solved exactly. The detailed calculations are as follows: First, we calculate exactly the retarded Green's functions for two independent quantum dots 1 and 2 under optical pumping. This process is very similar to that in Ref. [30], and the results are

$$g^{r}_{11,ee}(E_1, E_2) = \frac{2\pi\delta(E_1 - E_2)\, g^{0r}_{11,ee}(E_1)}{1 - \lambda^2 g^{0r}_{11,ee}(E_1)\, g^{0r}_{11,hh}(E_1 - \omega)} \equiv 2\pi\delta(E_1 - E_2)\, \tilde{G}^{r}_{11,ee}(E_1) \quad (12)$$

$$g^{r}_{22,ee}(E_1, E_2) = \frac{2\pi\delta(E_1 - E_2)\, g^{0r}_{22,ee}(E_1)}{1 - \lambda^2 g^{0r}_{22,ee}(E_1)\, g^{0r}_{22,hh}(E_1 - \omega)} \equiv 2\pi\delta(E_1 - E_2)\, \tilde{G}^{r}_{22,ee}(E_1) \quad (13)$$

where $g^{0r}_{11,ee}(E) \equiv 1/(E - \varepsilon_{e1} + i\Gamma_L/2)$, $g^{0r}_{22,ee}(E) \equiv 1/(E - \varepsilon_{e2} + i\Gamma_R/2)$, $g^{0r}_{11,hh}(E) \equiv 1/(E + \varepsilon_{h1})$, and $g^{0r}_{22,hh}(E) \equiv 1/(E + \varepsilon_{h2})$ are the electron and hole Green's functions for the quantum dots 1 and 2 in absence of the optical pumping. Note that we have assumed the wide-band approximation and regarded the couplings between the leads and quantum dots as two constant linewidth functions Γ_L and Γ_R. Once we have obtained $g^{r}_{11,ee}(E_1, E_2)$ and $g^{r}_{22,ee}(E_1, E_2)$, we go to the next step and derive the full Green's functions via the Dyson equation $G^{r} = \tilde{G}^{r} + \tilde{G}^{r}\Sigma^{r}G^{r}$,

$$G^{r}_{11,ee}(E_1, E_2) = \frac{2\pi\delta(E_1 - E_2)\, \tilde{G}^{r}_{11,ee}(E_1)}{1 - t^2\, \tilde{G}^{r}_{11,ee}(E_1)\, \tilde{G}^{r}_{22,ee}(E_1)} \quad (14)$$

$$G^{r}_{22,ee}(E_1, E_2) = \frac{2\pi\delta(E_1 - E_2)\, \tilde{G}^{r}_{22,ee}(E_1)}{1 - t^2\, \tilde{G}^{r}_{11,ee}(E_1)\, \tilde{G}^{r}_{22,ee}(E_1)} \quad (15)$$

$$G^{r}_{12,ee}(E_1, E_2) = \frac{2\pi\delta(E_1 - E_2)\, \tilde{G}^{r}_{11,ee}(E_1)\, t\, \tilde{G}^{r}_{22,ee}(E_1)}{1 - t^2\, \tilde{G}^{r}_{11,ee}(E_1)\, \tilde{G}^{r}_{22,ee}(E_1)} \quad (16)$$

3 Results and discussion

Substituting all of the above relations into Eq. (11), we finally obtain

$$I_L = q\int \frac{dE}{2\pi} T(E)\{f_R(E) - f_L(E)\} \quad (17)$$

where $T(E) \equiv \dfrac{\Gamma_L \Gamma_R t^2 |\tilde{G}^{r}_{11,ee}(E)|^2 |\tilde{G}^{r}_{22,ee}(E)|^2}{|1 - t^2 \tilde{G}^{r}_{11,ee}(E)\, \tilde{G}^{r}_{22,ee}(E)|^2}$.

Equation (17), which is the central result of this work, expresses the dissipative current through two coupled semiconductor quantum dots under optical pumping in terms of two local retarded Green's functions. In Fig. 1, we plot the transmission coefficient $T(E)$ as a function of the energy E. There are four resonant peaks. To demonstrate

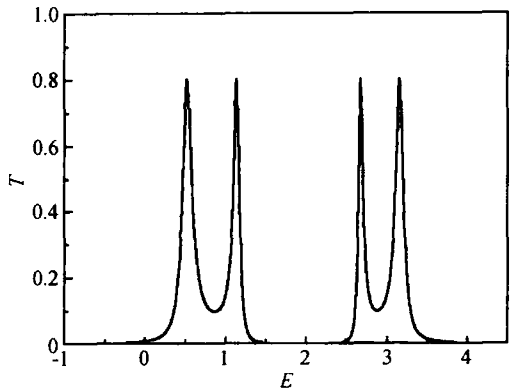

Fig. 1 Transmission coefficient T versus the energy E. We set the parameters as $\Gamma_L = \Gamma_R = 0.2$, $t = 0.5$, $\varepsilon_{e1} = 2$, $\varepsilon_{e2} = 1.5$, $\varepsilon_{h1} = \varepsilon_{h2} = 1$, $\lambda = 1$, and $\omega = 3$.

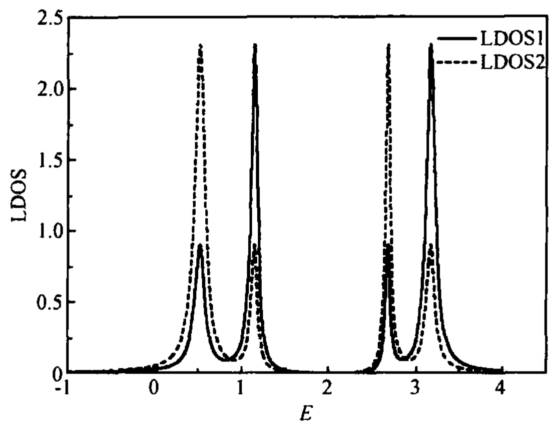

Fig. 2 Local density of states (LDOS) for quantum dot 1 (solid line) and dot 2 (dashed line). All the parameters are the same as in Fig. 1.

the physical original of these peaks, we plot the electron's local density of states ($\mathrm{LDOS} \equiv -\frac{1}{\pi} \times \mathrm{Im}G^{r}$) for two quantum dots. We find that the poles of the Green's function exactly determine both the positions of the transmission resonance peaks in Fig. 1 and those of the peaks in LDOS. Figure 3 shows the current-voltage curves for different optical pumping intensities. The I-V curves exhibit the well-known plateau shapes, and the charge currents decrease with increasing optical pumping intensity. In Fig. 4, we plot the transmission coefficient $T_{E=E_F=0}$ as a function of the optical pumping frequency. Surprisingly, there is a dip between the two resonant tunneling peaks when the frequency of optical pumping (relative to the Fermi level of the leads) equals the discrete energy level of holes in the quantum dots. This result can be understood from the expression of the zero energy transmission coefficient $T_{E=E_F=0}$:

$$T_{E=E_F=0} = \frac{\Gamma_L \Gamma_R t^2}{\left| \left(\varepsilon_{e1} + \frac{\lambda^2}{\varepsilon_{h1} - \omega} - i\Gamma_L\right)\left(\varepsilon_{e2} + \frac{\lambda^2}{\varepsilon_{h2} - \omega} - i\Gamma_R\right) - t^2 \right|^2} \tag{18}$$

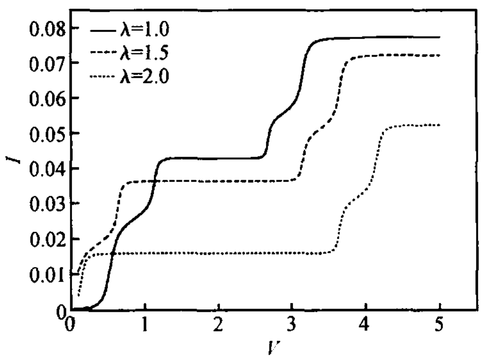

Fig. 3 Charge current versus voltage at zero temperature for different optical pumping intensities $\lambda = 1.0$ (solid line), 1.5 (dashed line), and 2.0 (dotted line) All the parameters are the same as those in Fig. 1.

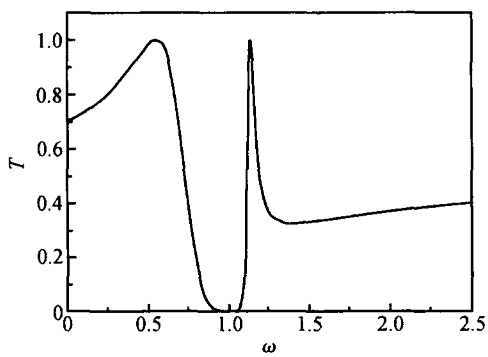

Fig. 4 Transmission coefficient $T(E = E_F = 0)$ versus optical pumping frequency ω We set the parameters as $\Gamma_L = \Gamma_R = 0.5$, $t = 0.8$, $\varepsilon_{e1} = \varepsilon_{e2} = 0.4$, $\varepsilon_{h1} = \varepsilon_{h2} = 1$, $\lambda = 0.4$.

We also have following physical arguments: At zero temperature, only the electrons at the Fermi energy level participate in the transport. These electrons entering the quantum dots from the leads will resonate with the holes in quantum dots under the optical pumping frequency $\omega = \varepsilon_{h1}$ or ε_{h2}, leading to the dynamical localization of electrons. This interesting result can be used to design optical control switches.

4 Conclusion

In summary, we have theoretically investigated the electron transport properties of two coupled semiconductor quantum dots under optical pumping. By using the Keldysh-Green formalism, we have solved the time-dependent quantum transport problem analytically. Plateau structures in the I-V curves occur and can be explained by the local electron density of states in quantum dots. We have also studied the effects of the optical pumping frequency and intensity on the transport properties of the system. When the frequency of the optical pumping is equal to the discrete hole energy level, the electron dynamical localization phenomenon occurs. This result can be used to realize optical control switching. Since optical controls possess several advantages over control by gate voltage for example, ultrafast lasers can control quantum systems on the femtosecond time scale, and with shaping techniques the amplitude and phase of the pulses can be designed at will and offer a great deal of flexibility and efficiency[31]. We hope this work will further stimulate the research of semiconductor optical control nanostructures.

Acknowledgement The authors would like to thank the support of the NCET.

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光学泵作用下两个耦合量子点的输运性质*

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摘要: 运用 Keldysh 格林函数,理论研究了在光学泵作用下的两个耦合量子点的电子输运性质. 发现了电流-电压曲线上的平台结构以及透射系数的共振峰,可以由量子点的局域态密度来解释. 讨论了光学泵的频率以及强度对系统输运性质的影响,发现当光学泵的频率等于空穴的分立能级时,发生电子的动力学局域化. 这个结果可以用来实现光学控制开关.

关键词: 格林函数; 光学泵; 量子点; 电子输运; 动力学局域化

PACC: 7200; 7320D

中图分类号: O472$^+$.4　**文献标识码**: A　**文章编号**: 0253-4177(2006)04-0598-06

* 国家自然科学基金资助项目(批准号:90303011,10474034,60390070)

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2005-12-14 收到,2006-01-25 定稿